High-Resolution Sequence Stratigraphy of the Middle Jurassic Lower Fadhili Reservoir in Khurais Complex, Central Saudi Arabia

BY

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This thesis, written by Abdullah Saad Ibrahim Al-Mojel under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN GEOLOGY.

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DEDICATION

To

My father Saad Ibrahim Al-Mojel,

and to my mother Norah Hamad Al-Mojel

ACKNOWLEDGMENTS

All praise to almighty ALLAH, the most Merciful and the most Benevolent, who gave me the chance, talent and time to achieve this work.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ENCLOSURES

THESIS ABSTRACT

NAME OF STUDENT: Abdullah Saad Brahim Al-Mojel

TITLE OF STUDY: High-Resolution Sequence Stratigraphy of the Middle Jurassic Lower Fadhili Reservoir in Khurais Complex, Central Saudi Arabia

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The Middle Jurassic Lower Fadhili Carbonate Member of the Dhruma Formation in Khurais Field is composed of two composite sequences which in ascending stratigraphic order are: Lower Fadhili composite sequence 1 (LFC1); and Lower Fadhili composite sequence 2 (LFC2). Each composite sequence is composed of four high-frequency sequences (HFS).

This study is based on detailed sedimentological descriptions of nine cored wells, a total of 370.9 meters (1,217 feet). The sequences of the Lower Fadhili reservoir are made up of five facies. The facies (in order from proximal to distal) are: skeletal coated-grain grainstone upper shoreface, peloid coated-grain grainstone and packstone lower shoreface, *Thaumatoporella* wackestone inner lagoon, stromatoporoid wackestone/packstone outer lagoon, and *Pfenderina trochoidea* wackestone/mudstone transgressive lagoon. There are two more facies have been recognized from Lower Fadhili cores and are not genetically related to the Lower Fadhili reservoir facies and sequences. These facies are: argillaceous mudstone and calcareous shale marginal marine and cemented ooid coated-grain intraclast grainstone beach facies.

The base sequence boundary of the Lower Fadhili reservoir, the base of LFC1, overlies a subaerial exposure (karst) surface on top of the ooid coated-grain intraclast grainstone beach facies that contains meteoric calcite cement, which is evidence for an exposure surface and a potential unconformity. The top sequence boundary of the Lower Fadhili reservoir (top of LFC2) is marked by a major subaerial exposure surface (karst), filled from the above by the green calcareous shale facies (reservoir seal).

Fining-upward small-scale cycles of the first composite sequence (LFC1) of the Lower Fadhili reservoir onlapped onto the unconformity. These cycles are dominated by *Pfenderina trochoidea* wackestone facies and stromatoporoid packstone/wackestone facies. The maximum flooding surface (MFS) can be traced across the fields and it coincides with a thin layer of *Pfenderina trochoidea* wackestone facies. In the highstand systems tract (HST), the abundance of *Pfenderina trochoidea* decreases upwards and the abundance of sponge spicules and *Thaumatoporella* increases upwards.

The second composite sequence (LFC2) highstand was dominated by fining-upward cycles of stromatoporoid packstone/wackestone facies, shallow marine lagoonal wackestone and shoreface coated-grain grainstone. *Thaumatoporella* and *Cladocoropsis* are abundant in the lagoonal wackestones. Toward the top of the HST of the second composite sequence (LFC2), the abundance of *Thaumatoporella* increases and the abundance of stromatoporoid decreases upward. Bedding in the HFS thinned upward and was capped by a subaerial exposure (karst) surface at a sequence boundary.

The Lower Fadhili was deposited in a shallow marine, tropical intra-shelf basin. The Lower Fadhili carbonate reservoir is overlain and underlain by green marls (reservoir seal).

The dominant porosity type of the Lower Fadhili reservoir facies is microporosity, except that the coated-grain grainstone and packstone facies has an interparticle porosity. The peloid coated-grain grainstone and packstone facies has the best reservoir quality because the interparticle porosity is well connected.

The use of high-resolution sequence stratigraphy of the Lower Fadhili reservoir has been beneficial to reservoir characterization and geological modeling.

ملخص الرسالة

الاســـــــم: عـبـد الله بن سـعـد أبراهيم الـمـعـجـل

عنوان الرسالة: الوصف العالي الوضوح للمتتابعات الطبقيه الزمنية لمكمن فاضلي السفلي البترولي من منتصف العصر الجوراسي في منطقة خريص, وسط المملكة العربية السعودية
التـخـصــص: الجيـــولـوجيـــــا

تاريخ التخرج: مايو 2010

فاضلي السفلي الجيري عضو من متكون ضرما في العصر الجوراسي الموجود في جوف منطقة خريص ويتكون من وحدتين من التتابع الطبقي الزمني المركب الذي يتكون من تتابعات صغيرة ناعمة تصاعدياً كثيرة التكرار. تعتمد هذه الدراسة على سجلات رسوبية تفصيلية لتسع أبار قطعت فيها عينات صخرية اسطوانية بلغ طولها الإجمالي 370.9 متر (1,217 قدم). مكمن فاضلي السفلي ترسب في مياه بحرية ضحلة, في حوض ترسيب إستوائي في وسط رصيف قاري. يحد المكمن البترولي لفاضلي السفلي من الأعلى ومن الأسفل بطبقة تتكون من طفلة جيرية خضراء. الجزء الأساسي من خزان فاضلي السفلي الجيري البترولي يتكون في الغالب من صخر واكي و مرصوص مع عدة طبقات رقيقة من صخور حبيبية أطبِق عليها بأسطح صلبه و/أوشبه صلبه.

الجزء السفلي من منطقة الدراسة يتكون من سحنتين: سحنة طينية رملية جيرية وسحنة شاطئية حبيبية مكونة من قطع جيرية معادة الترسيب وسرئيات. الحفر البيولوجية جحور "الكوندرايتي" تتواجد فقط في السحنة الطينية الرملية الجيرية. الرخويات البطنقدمية تتواجد بكثرة في سحنة الشاطئ الحبيبية المتكونة من قطع جيرية معادة الترسيب وسرائيات. التتابع الطبقي لهذة السحنات مطبوقة بسطح عدم توافق تميز بسطح إنكشافي, سطح صلب. سحنة الشاطئ الحبيبية المتكونة من قطع جيرية

نهايات التتابعات كثيرة التكرار الناعمة تصاعدياً لتتابع الطبقي المركب الأول تنتهي على سطح عدم التوافق بشكل أفقي و تصاعدي. غالبية سحنات التتابعات الكثيرة التكرار لتتابع الطبقي المركب الأول هي سحنات واكية يكثر فيها نوع من أنواع الفورامنيفرا ويسمى "فاندارينا تروكويديا" وسحنة مرصورة/واكية يكثر فيها نوع من أنواع الأسفنجيات المرجانية "الستروماتوبورويد". مستوى الحد الأعلى للفيضانات يمكن تتبعه وتحديده على طول الحقول ويتزامن مع طبقة رقيقة من السحنة الواكية التي يكثر فيها نوع من أنواع الفورامنيفرا "فاندارينا تروكويديا". في مسار الأنظمة الإنحساري (HST) للتتابع الطبقي المركب الأول, وفرة الفورامنيفرا "فاندارينا تروكويديا" تتضائل تتدريجياً صعوداً للأعلى ووفرة الأسفنج الشوكي و الطحالب الخضراء "ثوماتوبريلا" تتزايد صعوداً للأعلى.

مسار الأنظمة الإنحساري (HST) للتابع الطبقي المركب الثاني تهيمن عليها تتابعات كثيرة التكرار ناعمة تصاعدياً تتكون من سحنات عدة منها سحنة الأسفنجيات المرجانية "الستروماتوبورويد" الواكيه/المرصوصه و سحنة مستنقعات بحرية واكيه ضحلة وسحنة وجه الشاطئ الحبيبي ذو الحبيبات المغلفة. الطحالب الخضراء "ثوماتوبريلا" والإسفنجيات الكلسية "كلادوكوروبسيس" متوفرة بكثرة في سحنات المستنقع البحري الواكي. تتزايد وفرة الطحالب الخضراء "ثوماتوبريلا" وتتضائل وفرة الإسفنجيات المرجانية "الستروماتوبورويد" كلما إتجهنا للأعلى من مسار الأنظمة

الإنحساري (HST) لتتابع الطبقي الثاني. التتابعات الكثيرة التكرار في مسار الأنظمة الإنحساري (HST) لتتابع الطبقي الثاني تترقق كلما صعدنا للأعلى ومطبوقة بسطح كارستي يتميز بذوبان الحجر الجيري على سطحة.

CHAPTER 1

INTRODUCTION

This study defines the high frequency sequence stratigraphic framework, facies distribution, depositional environment, and platform model of the Middle Jurassic Lower Fadhili reservoir of the Dhruma Formation in the Khurais complex of oil fields (Figure. 1.1).

The Khurais complex consists of three fields: Khurais, Mazalij and Abu Jifan. Khurais field is the second largest onshore oil field in Saudi Arabia and was discovered in 1957. The Khurais field has three oil-bearing reservoirs arranged from younger to older: Arab-D, Hanifa, and Lower Fadhili. All of these reservoirs are composed of carbonate rocks and are Jurassic in age. To date, the Lower Fadhili reservoir has not been produced.

Development of Khurais complex is the largest industrial oil project in the world and the largest oil increment in Aramco's history. The increment will add 1.2 million barrel per day to maintain and supply the global oil market. The Lower Fadhili reservoir has not been produced and will be on standby to maintain the incremental production in the future. The reservoir quality of the Lower Fadhili is defined as poor to moderate reservoir quality. Therefore, defining the fluid flow units and good reservoir facies within the high frequency sequence stratigraphic framework will facilitate reservoir development studies.

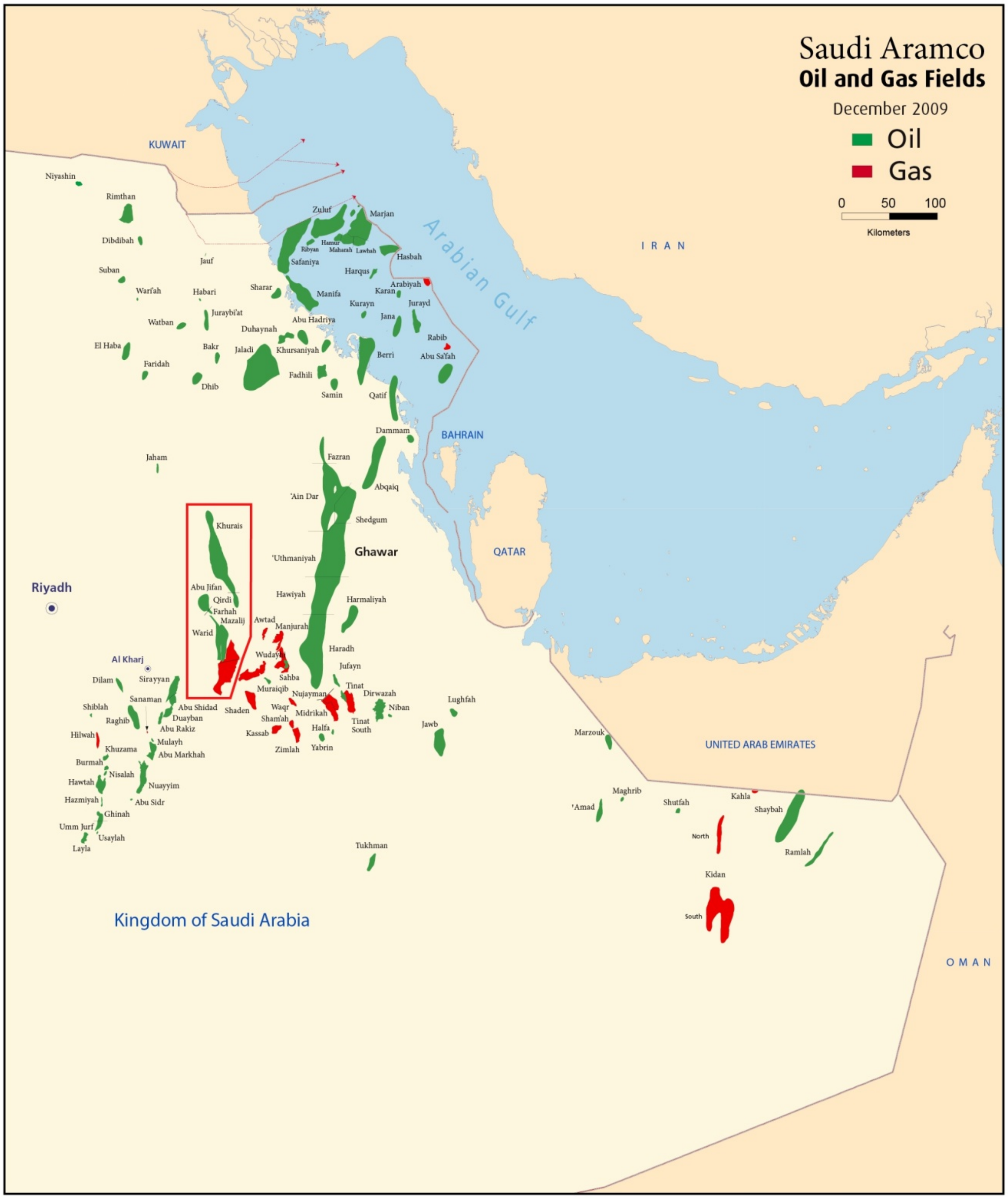


Figure 1.1. Map showing the location of Khurais Field (within the red polygon). The petroleum fields are shown here in color (green and red).

1.1. OBJECTIVE OF THE STUDY

The main goals of this study are as follows:

- Build high-resolution sequence stratigraphy of the Lower Fadhili reservoir in the Khurais complex.
- Identify and describe facies and create depositional model of the Lower Fadhili reservoir in the Khurais complex
- Correlate reservoir and seal facies within the defined high-resolution sequence stratigraphic framework.

The justification for the high frequency sequence stratigraphy study of the Lower Fadhili reservoir is to provide a framework of the reservoir as a base for geological modeling and/or reservoir development studies. The facies and the rock units of the reservoir in the framework can be in the end mapped out in time and space and are predictable. To do so, there are a few requirements that need to be accomplished: core should be carefully described the cyclicity and the rock succession should be interpreted, picked, and correlated, and the depositional environment should be understood. The following objectives are stated in order to achieve the requirements of this goal:

- Describe cores with good recovery and thin sections of the reservoir.
- Define facies and the depositional environment model of the Lower Fadhili succession.
- Define significant stratigraphic surfaces and rock contacts.
- Understand the main control on the depositional cycles.
- Set criteria for picking the depositional cycles.

- From core description pick the depositional cycles and correlate them by creating a framework of time lines between the cored wells.
- Correlate the facies and the genetically related packages within the framework.
- Identify stacking patterns of the depositional cycles and the sequence stratigraphy hierarchy.
- Identify the system tracts within the framework.
- Identify composite sequence boundaries.

1.2. LOCATION OF THE STUDY

The Khurais complex is located in the central part of Saudi Arabia about 160 km east of Riyadh. The Khurais structure is a north-south trending asymmetrical anticline. The eastern flank contains a 2° dip, while the steep western flank contains average dip of 8.7°. The Khurais field trend is 127 km from north to south and the width ranges from 5-17 km (Al-Afaleg, et al. 2002).

The Dhruma Formation is Lower Bajocian to Upper Bathonian in age. The Dhruma Formation resting unconformably atop the Marrat Formation and is unconformably overlain by the Tuwaiq Mountain Formation (Figure. 1.2) (Hughes, 2006). The Lower Fadhili reservoir is equivalent to the upper part of zone D6 unit of the Middle Dhruma Formation (Lindsay R.F. et al, 2008). The age of the D6 unit is Late Bathonian. During that time, the Lower Fadhili reservoir in the Khurais complex was deposited upon a carbonate ramp and intrashelf basin within the Arabian Platform called the Arabian Basin (Figure. 1.3).

The Lower Fadhili reservoir in the Khurais complex is about 48 meters (157 feet) thick. The number of wells that were studied in the Khurais complex is nine wells, here in named wells A, B, C, D, E, F, G, H, and I. These wells have the most complete cored interval in Khurais complex, covering the Lower Fadhili reservoir. The wells are presented in two cross sections. The main cross section is 119 km in length and consists of seven wells A, B, C, D, E, F, and G. The second cross section is 60 km in length and consists of three wells H, C, and I (Figure. 1.4). A total length of 370.9 meters (1,217 feet) of core from nine wells was described for this study.

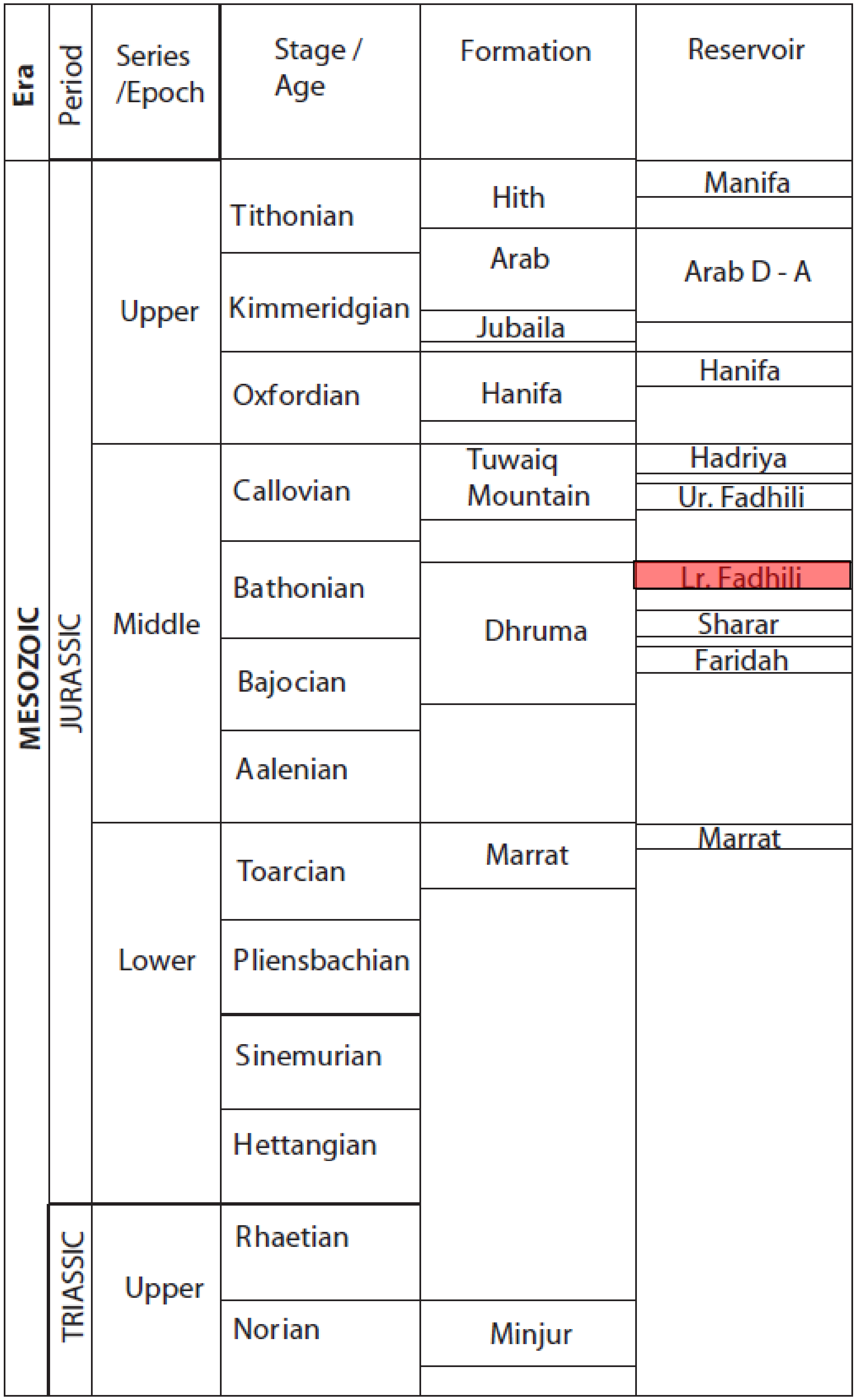


Figure 1.2. Stratigraphic column showing the age of Lower Fadhili Reservoir (Hughes, 2006)

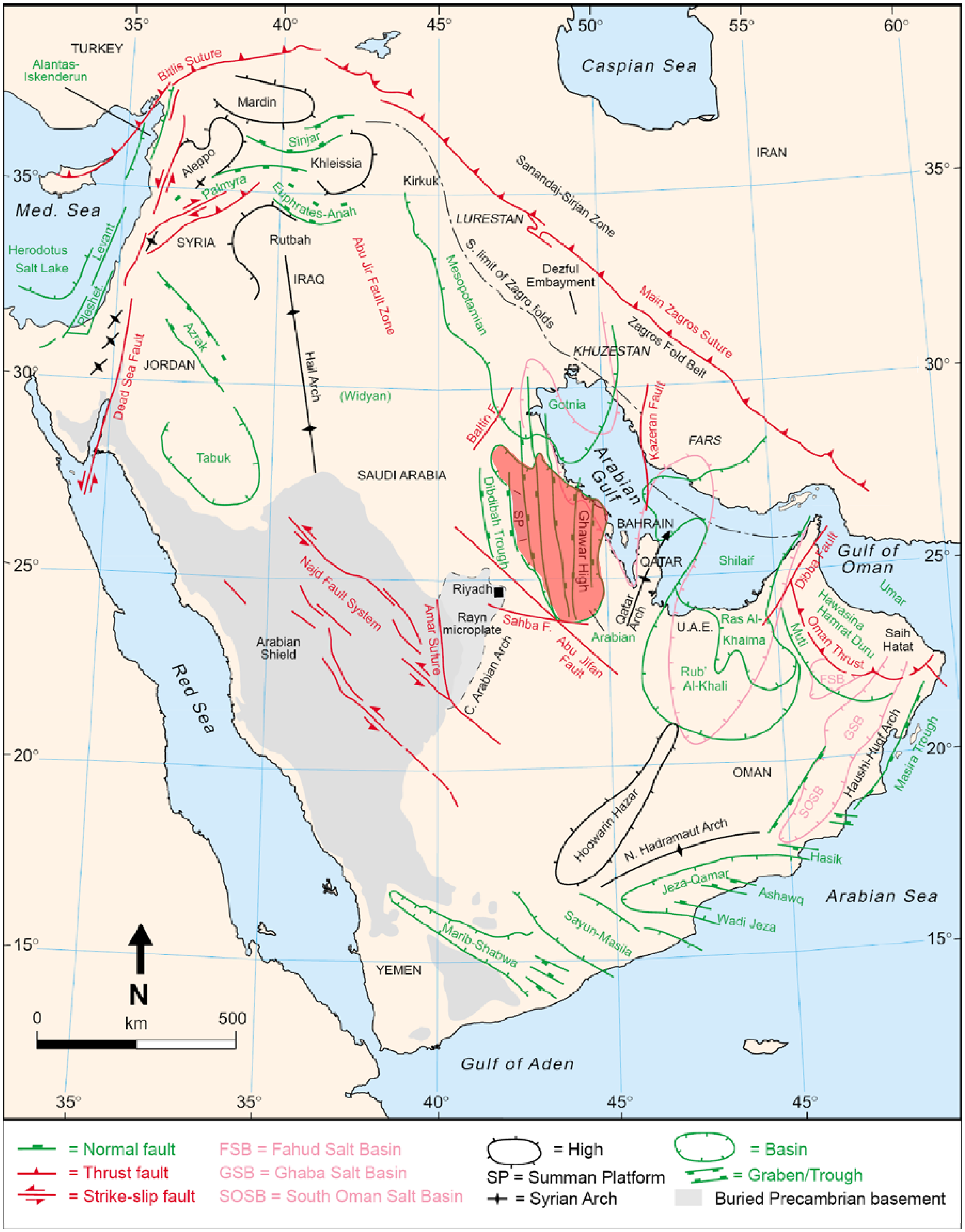


Figure 1.3. Map showing structural interpretation of Arabian Plate and the location of intra-shelf basins (Ziegler, 2001). The Arabian basin, where Khurais and Ghawar fields are located, is colored.

Khurais Complex

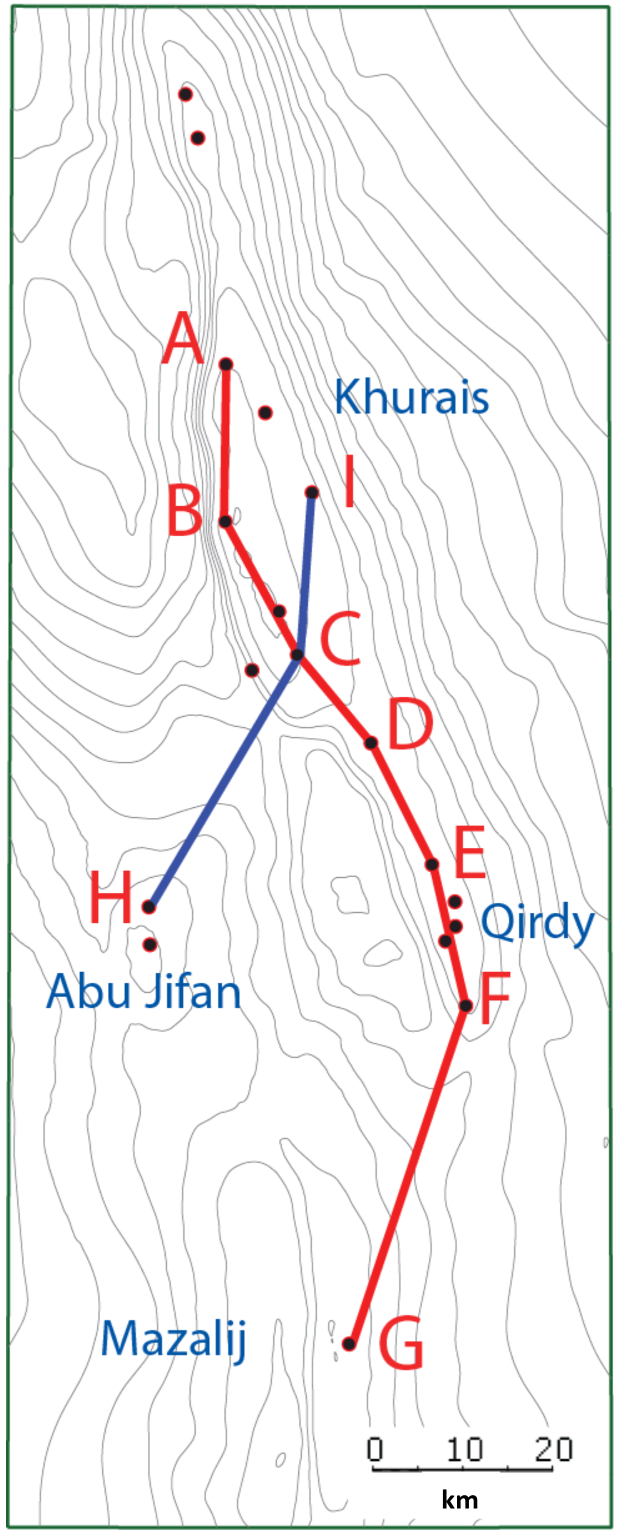


Figure 1.4. Map of Khurais complex showing the fields and the cored wells. The red line is the traverse of the main cross section and the blue line is the second traverse.

1.3. PREVIOUS WORK

Lithology: Max Steineke in 1937 was the first geologist to define the Dhruma units in an outcrop in central Saudi Arabia. The Dhruma Formation is named after the town of Durma near the middle of the outcrop (Powers et al., 1966). The type section of Dhruma Formation was measured and described by Steineke, et al. (1958). The Dhruma Formation was divided into three units: lower Dhruma, middle Dhruma, and upper Dhruma. The Lower Dhruma consists of calcarenitic limestone with interbedded shale and olive-green gypsiferous shale. The Middle Dhruma is mainly composed of brown oolite beds. The Upper Dhruma consists of olive calcareous clay shale interbedded with white chalky limestone (Steineke et al., 1958).

Powers et al. in (1966) divided the upper Dhruma into two members: The lower Atash Limestone Member and the upper Hisyan Shale Member (M. Moshrif, 1987). This division was based on lithologic and faunal data. The Lower Fadhili Reservoir in the subsurface of eastern Arabia was interpreted to be equivalent to the Atash Member by Powers et al. (1966).

Manivit et al. (1990), as part of the geological mapping project conducted in the 1980s-1990s by the Saudi Geological Survey and French Geological Survey, divided the Dhruma Formation into seven informal members D1 to D7. These members are, from older to younger, the Balum (D1), Dhibi (D2), Jufayr (D3), Uwaynid (D4), Barrah (D5), Mishraq (D6), Atash, and Hisyan (D7). The D1 and D2 members are in lower Dhruma. The D3 to D6 members are in the middle Dhruma, and the D7 member is in the upper Dhruma (Hughes, 2006). Hughes (2006) assigned the D7 member, including Atash and

Hisyan (Upper Dhruma Formation), to the Tuwaiq Mountain Formation because the D7 is a mud dominated backstepping, and deepening assemblage that is genetically related to the basal Tuwaiq Mountain Formation. Lindsay et al. (2008) found that the upper part of zone D6 is equivalent to the Lower Fadhili reservoir in eastern Saudi Arabia instead of being equivalent to the Atash member. This correlation was based on sequence stratigraphy and microbiofacies analysis.

Sequence Stratigraphy: A global eustatic cycle chart of sea-level changes for the Mesozoic and Cenozoic was established by Haq et al. (1988). Based on that chart, the concept of sequence stratigraphy was proposed for the first time for the Middle and Upper Jurassic of central Saudi Arabia outcrops by Le Nindre et al. (1990) and Vaslet el al. (1991). Al-Husseini (1997) followed the same approach and laterally correlated the Jurassic sequence stratigraphy for the Arabian Gulf countries based on stratigraphic and biostratigraphic considerations. Sharland et al. (2001; 2004) established and interpreted 63 maximum flooding surfaces for intervals upon the Arabian Plate. Le Nindre et al. (2003) recognized for the first time tectonic features that controlled sedimentation on the Arabian Plate from the Permian to Tertiary. Haq and Al-Qahtani (2005) presented a regional cycle chart of sea-level changes affecting the Arabian Platform. Hughes (1996, 2004a, b, c, 2006) and Hughes et al. (2008) studied the biostratigraphy, biofacies, and palaeoenvironments of the Jurassic of Saudi Arabia.

Énay et al. (2009), the most recent study, reinterpreted the sequence stratigraphy of the middle Dhruma based on the biostratigraphic data (Figure 1.5). Previous to the Énay et al. (2009) study, the middle Dhruma (D4-D6) was assumed to be a single unbroken depositional package without any significant hiatus. The only stratigraphic gap that was previously known is the boundary between middle Dhruma (D4-D6) and upper Dhruma (D6-D7). Based on the biostratigraphic interpretation, Énay et al. (2009) separated D5 and D6 units by upper Lower and Middle Bathonian Wadi Ad Dawasir "delta" followed by a hiatus in late Middle Bathonian. In addition, Énay et al. (2009) interpreted the Lower Bathonian shale in the middle of D5 to be a MFS and the upper part of D5 as a regressive systems tract capped by the Wadi Ad Dawasir "delta" followed by a hiatus. Moreover, Énay et al. (2009) interpreted the D6 and the lower part of D7 as a transgressive systems tract and the Middle Callovian in the middle of the Hisyan shale member as a MFS (Al-Husseini, 2009). Al-Husseini (2009) updated the Middle East Geologic Time Scale 2008 for the late Triassic and Jurassic units of Saudi Arabia. Al-Husseini (2009) interpreted that the Lower Bathonian MFS of Énay et al. (2009) corresponds to the Lower Bathonian MFS J30 of Sharland et al. (2001) and the Middle Callovian MFS of Énay et al. (2009) matches with Middle Callovian MFS J40 of Sharland et al. (2001). Figure 1.6 is the most recent stratigraphic column for Dhruma Formation of Saudi Arabia after Al-Husseini (2009).

Al-Dukhayyil (2007) described the facies and identified high-resolution sequence stratigraphy of Khuff A and B carbonate in the subsurface of Haradh area, Southern Ghawar field in Saudi Arabia, for his Master of Science thesis at KFUPM. The outline and the methodology of this study are similar to Al-Dukhayyil's Master of Science thesis (2007). Moreover, Al-Khaldi (2009) identified high-resolution sequence stratigraphy of Dam Formation, Lidam Area, in Saudi Arabia, for his Master of Science at KFUPM.

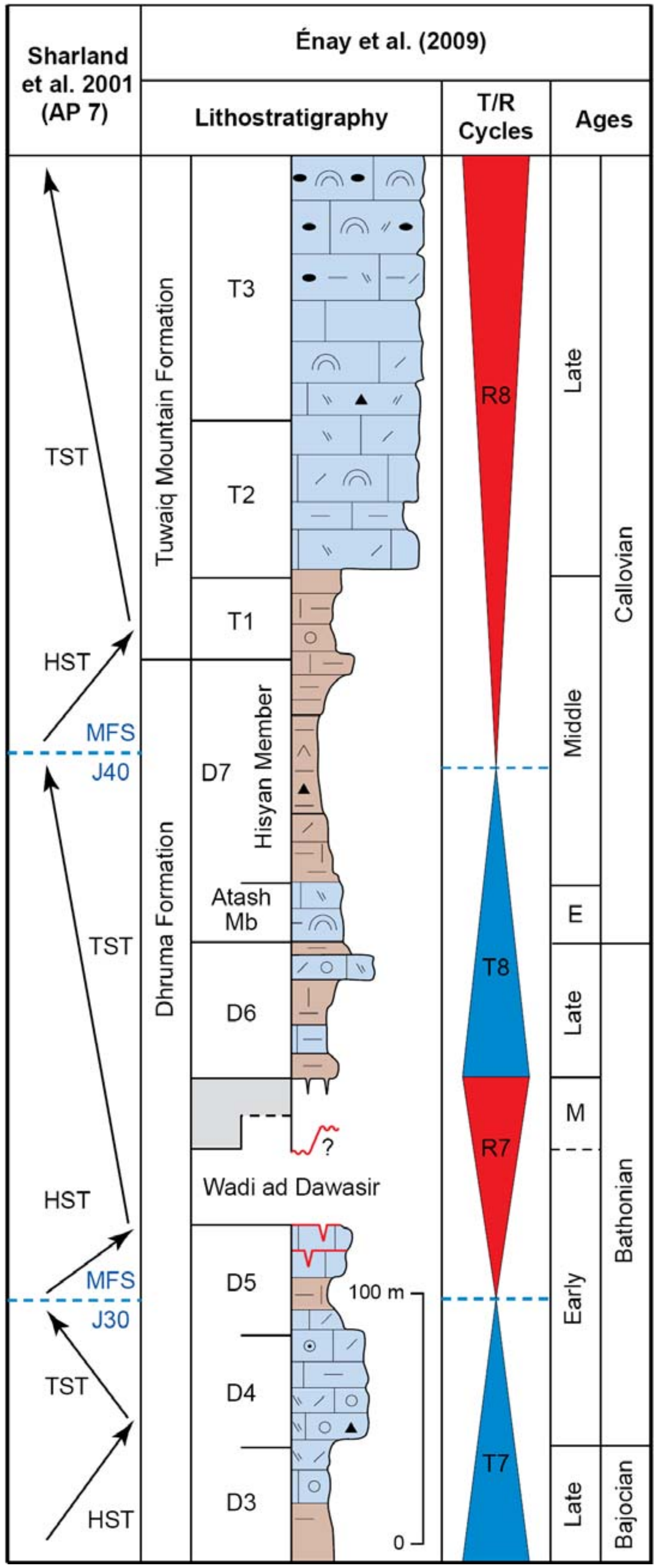


Figure 1.5. The most recent sequence stratigraphic interpretation for the outcrop of Middle Jurassic, in central Saudi Arabia, by Énay et al. (2009). The Lower Fadhili Reservoir in the Khurais complex is equivalent to the D6 (After Énay et al., 2009).

GEOLOGICAL TIME SCALE 2004					Arabian Plate		Formation		Member (Unit)	Reservoir
JURRASIC	MIDDLE	Callovian	M		J40	162.5	Dhruma Fromation	"upper"	Hisyan Member (D7)	
			E						Atash Member (D7)	
		Bathonian	L	164.7 ± 4.0				"middle"	D6 Unit	Lower Fadhili Reservoir
			M						Dawasir "delta"	
			E		J30	167.5			Mishraq Member (D5)	
									Barrah Member (D4)	? Sharar Reservoir
		Bajocian	L	167.7 ± 3.5				"lower"	Uwaynid Mber (D3)	? Faridah Reservoir
									Dhibi Lst Member (D2)	
			E		J20	171.0			Balum Member (D1)	

Figure 1.6. Stratigraphic column for Dhruma Formation showing Dhruma members and their reservoir equivalents, Geological Time Scale and the MFS of Sharland et al. (2001) (after Al-Husseini, 2009)

CHAPTER 2

GEOLOGIC SETTINGS

2.1. TECTONIC SETTINGS

Following Sharland et al. (2001), through geological time the Arabian Plate has evolved through five different tectonic settings called evolutionary phases. The evolutionary phases that Arabian Plate went through are: plate accretion, intra-cratonic, back-arc, passive margin plate settings, and active margin setting. The geological time intervals for each tectonic evolutionary phase are illustrated in (Figure 2.1). There are tectonic processes (e.g., inversion, uplift, rifting, flexing, etc.) associated with these evolutionary phases. These tectonic processes created regional unconformities in the stratigraphy of Arabian Plate. Sharland et al. (2001) linked the tectonic processes with large scale sequence of sediment that are bounded by regional and major unconformities and called them Tectonostratigraphic Megasequences. The stratigraphy of the Arabian Plate is divided into eleven Tectonostratigraphic Megasequences (AP1-AP11) by Sharland et al. (2001). The geological time intervals of the Tectonostratigraphic Megasequences are presented in (Figure 2.1) (Sharland et al., 2001).

The tectonic phase of the Mesozoic (mid-Permian to mid-Cretaceous) in the Arabian Plate was an extensional phase. The Mesozoic (mid-Permian to mid-Cretaceous) has three Tectonostratigraphic Megasequences (AP6-AP8). The Lower Fadhili reservoir of the Dhruma Formation is part of AP7 Tectonostratigraphic Megasequence that was formed in late Early Jurassic to Late Jurassic. AP7 is affected by two tectonic processes that created basal and top regional unconformities. The basal regional unconformity of AP7 is caused by major rifting at the northern part of the plate associated with the opening of the Mediterranean, which created large and new accommodation space as Neo-Tethys passive margin in the north. In additional, during that time there was rift shoulder uplift in Oman, the southern part of the plate, associated with rifting of the Indian Plate from Oman. The top regional unconformity of AP7 is caused by the spreading of Indian Plate from Oman followed by a relative fall in sea level (Sharland et al., 2001). All of these rifts happened outside the Arabian Plate and there were no rifts within the Arabian Plate during the Jurassic, except slight extensional faults system trends N-S that caused highs and lows in the eastern Arabian Plate (Énay et al., 2009).

In general, the accommodation space of the Arabian Plate was low and limited during the Phanerozoic and has been controlled by low subsidence, affected by the sediment loads, and by global eustatic changes. The subsidence rate for the Lower and Middle Dhruma Formation in the outcrop of Saudi Arabia was 48 m/Ma (Hughes, 2006). This rate is based on the absolute age and thickness of Dhruma Formation. This subsidence rate cannot be used for intrashelf basins. In general, the subsidence rate of the eastern Arabian Plate during Mesozoic was slow (Sharland et al., 2001).

Three intra-shelf basins in the eastern Saudi Arabia developed in the late Middle Jurassic (Late Callovian) to early Late Jurassic (Middle Oxfordian) due to subsidence of the basement blocks. The subsidence was caused by slight extension in the N-S main fault systems (Sharland et al., 2001). The main structural trends associated with N-S extensional faults were the Summan Platform, Dibdibah Trough, Khurais-Burgan Anticline, Ghawar-Safaniya Anticline, and Qatar Arch (Figure. 1.3) (Ziegler, 2001).

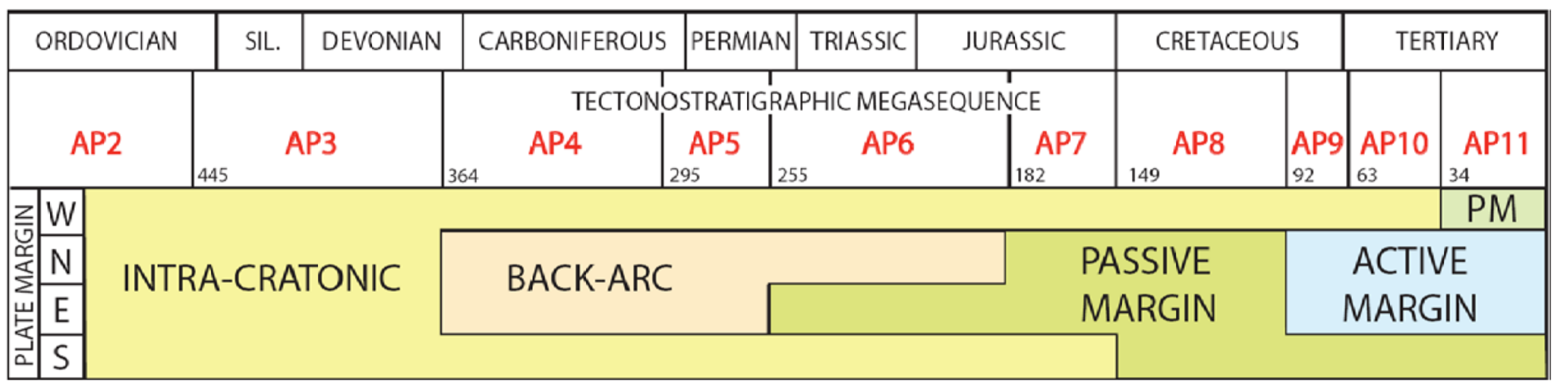


Figure 2.1. Geological time scale showing time intervals for the tectonic evolutionary phases of the Arabian Plate and the Tectonostratigraphic Megasequence of Sharland et al. (2001). (After Sharland et al., 2001)

2.2. PALEOGEOGRAPHY

During the Jurassic, the Arabian Plate was located in an equatorial location (Sharland et al., 2001). Arabian Shelf was located in the southern margin of the Neo-Tethys Ocean (Hughes, 2004) (Figure. 2.2). According to the paleogeographic map provided by Énay et al. (2009) (Figure. 2.3), Khurais complex was located approximately 10° south of the equator during Middle Callovian time.

The northern and the eastern side of the Arabian Shelf were part of a passive margin during the Jurassic and part of a tropical shallow carbonate marine environment (Hughes, 2004). The Arabian Shelf was platform that was nearly horizontal to a gentle slope dipping toward north-northeast (Sharland el al., 2001). During the Middle and Late Jurassic, there were four intrashelf basins that developed within Arabian Shelf. The intrashelf basins that located in the eastern side of the shelf are Arabian Basin, Gotnia Basin, Rub' Al-Khali and Ras al Kaimah basins (Figure. 1.3) (Ziegler, 2001). The intrashelf basins were partitioned by paleotopographic highs (e.g., Qatar Arch, Rimthan Arch) and slightly restricted the basins from the open marine environment.

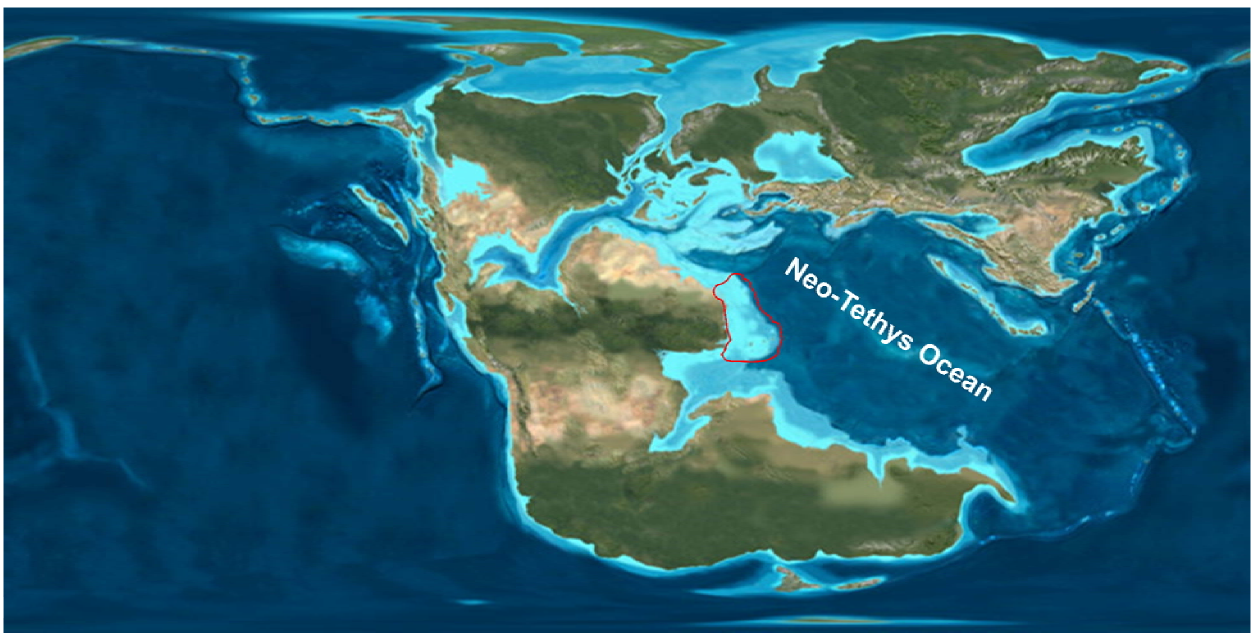


Figure 2.2. Paleogeographic map for Jurassic time shows the Arabian Platform (highlighted by red line) and the Neo-Tethys Ocean. The Arabian Platform was located in an equatorial latitude and formed the western margin of the Neo-Tethys Ocean (After Ron Blakey website). The red outline is the Arabian platform.

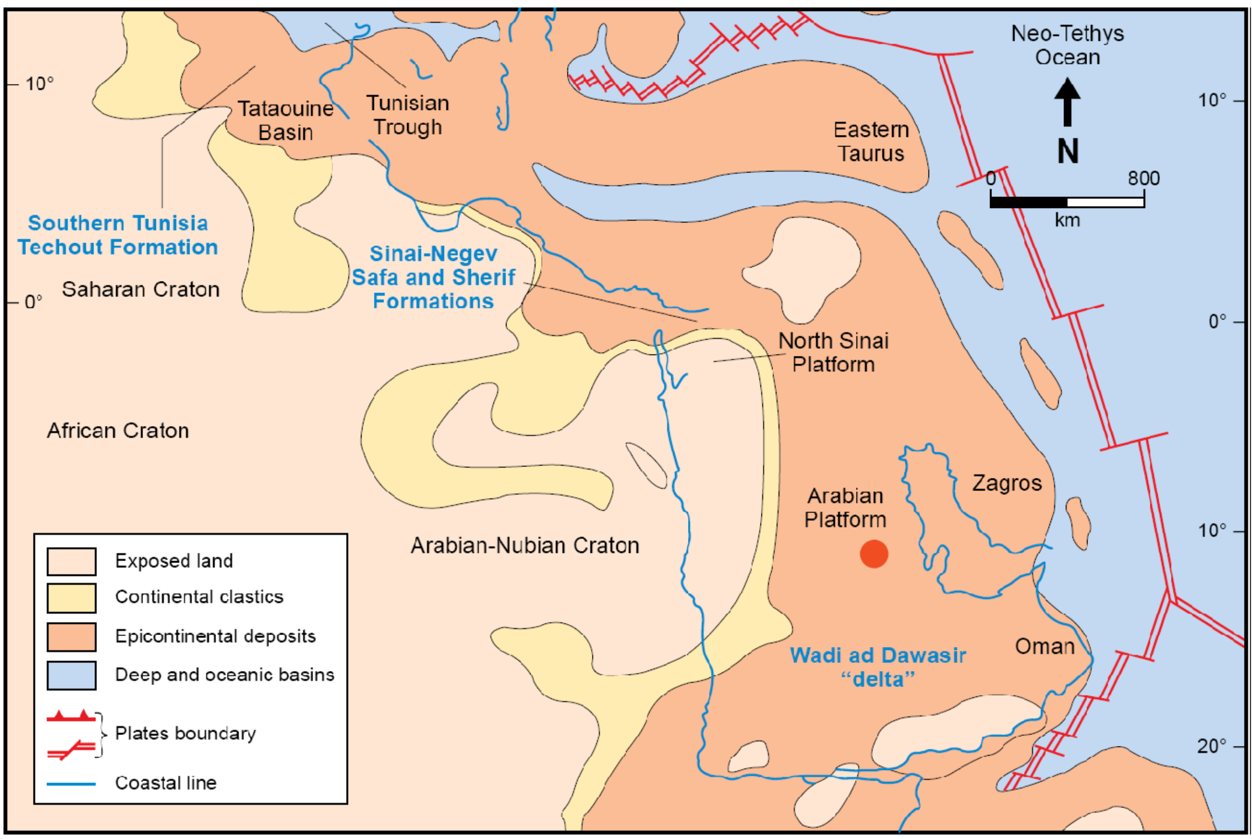


Figure 2.3. Detailed paleogeographic map for the Middle Callovian. This map shows the boundary of the Arabian Plate (red lines), Arabian Platform/Shelf and the margin of the Arabian Shelf. The red dot is the proximal location of Khurais complex in the Arabian shelf. Khurais complex was located approximately 10° south of the equator during the Middle Callovian (After Énay et al., 2009).

2.3. PALEOFACIES AND PALAEOENVIRONMENTS OF THE MIDDLE JURASSIC (BAJOCIAN TO BATHONIAN)

There was a major change in the regional facies patterns between the Early and Middle Jurassic of the Arabian Plate. During the Early Jurassic the Arabian Plate was dominated by carbonate-evaporite facies, especially in the northwestern side of the platform, and by siliciclastic facies in the Rub' Al-Khali Basin where the platform of the Middle Jurassic was a site of a vast carbonate platform with rare evaporites deposits (Murris, 1980; Ziegler, 2001). The change of the regional facies between Early and Middle Jurassic was due to two reasons: 1) eustacy, and 2) climate change. The Early Jurassic was a time of global lowstand of sea level (Haq et al. 1988), where as the Middle Jurassic (Bajocian to Bathonian) was a time of overall deepening and transgression (sea level rise) (Ziegler, 2001). The climate of the Middle Jurassic has been interpreted to have been humid (Murris, 1980).

The organisms associated with the tropical shallow carbonate sediments were very productive during Middle Jurassic. The carbonate sediment rapidly filled accommodation space during highstand systems tract (HST). Since the subsidence rate of the Arabian Platform was slow during the Mesozoic (Sharland et al., 2001) and the type of the platform was a carbonate ramp setting with a very gentle slope, the relative sea-level change was the main reason for rapid vertical changes of facies and associated sudden horizontal shifts of the depositional environment. Therefore, the somewhat "layer-cake" succession was the product of the relative sea-level changes (Sharland et al., 2001). The 5th and 4th order sequences - the reservoir scale parasequence level - may show gentle onlap, downlap or offlap relationships especially around the edge of the intra-shelf basins and the paleotopographic highs (Sharland et al., 2001).

Following Ziegler (2001), the prevailing Middle Jurassic (Bajocian to Bathonian) facies of the Arabian Platform are (in order from proximal to distal): coastal siliciclastics, shallow-marine shales, and shallow-marine detrital carbonates (Figure. 2.4). Dhruma Formation biocomponents studies show the depositional environment to have been a moderately shallow lagoonal setting with local stromatoporoid buildups (Hughes, 2006).

The intra-shelf basins and their surrounding carbonate ramps had an impact on the distribution of facies and the depositional environment of the Arabian Platform. For example, the Dhruma Formation regionally thinned (approximately 300m of section missing) from the Arabian Basin toward the Gotnia Basin (Ziegler, 2001). The equivalent member to the Lower Fadhili reservoir in the offshore of United Arab Emirates and Qatar is the Uweinat Member. The Uweinat Member in the offshore of Abu Dhabi and Qatar is made up of two units: the lower unit consists mainly of cross-bedded oolitic grainstone and the upper unit consists mainly of fine peloidal wackestone and packstone with reworked stromatoporoids (de Matos, 2002). The depositional environment of the Uweinat Member of the northern offshore Abu Dhabi is interpreted to be partially restricted oolite shoal barriers by de Matos (2002). The paleotopography of Qatar and offshore Abu Dhabi seems high the Bathonian and acted as a barrier to the intra-shelf basins (e.g., Arabian Basin).

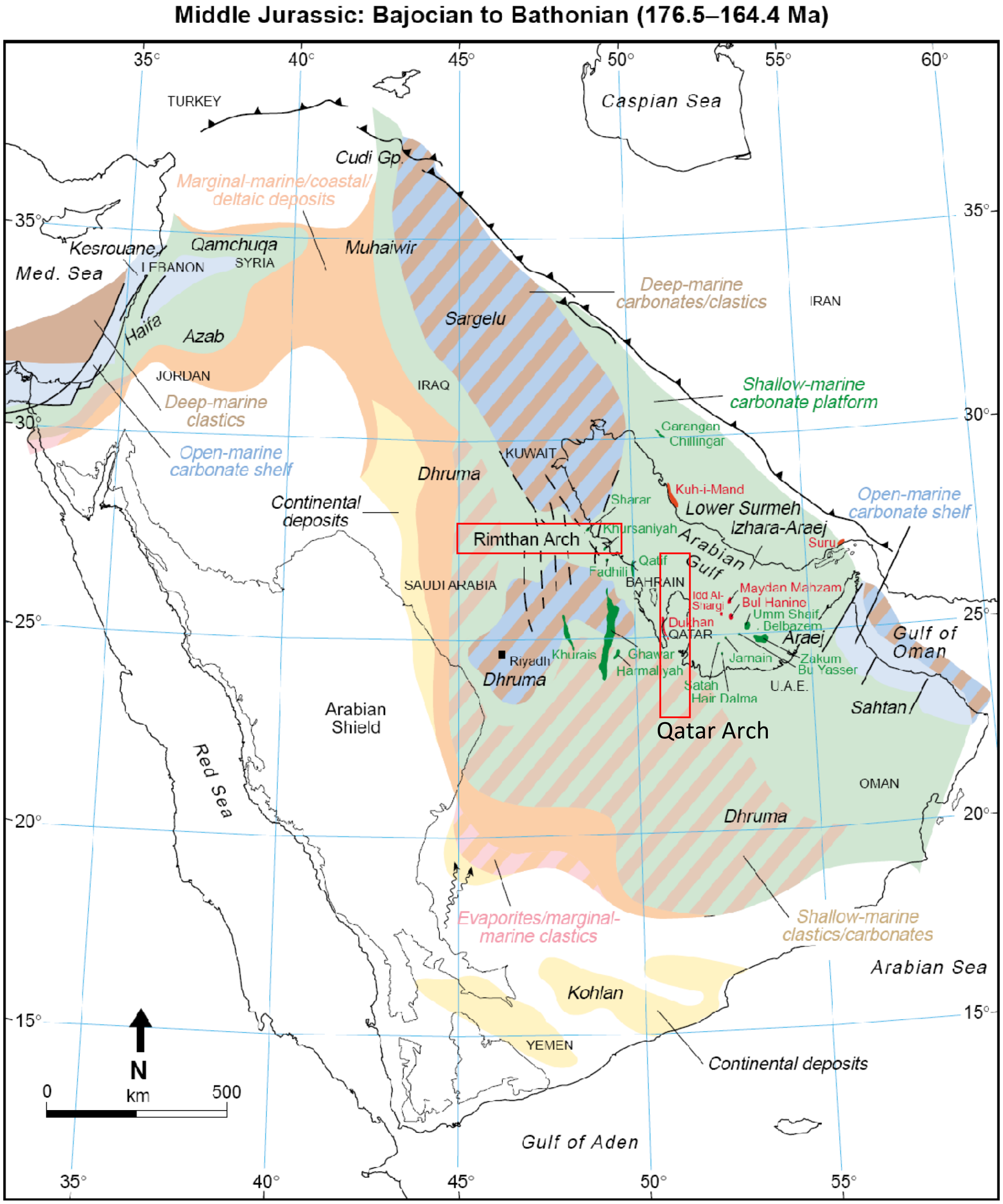


Figure 2.4. Paleogeography and facies map for the Middle Jurassic (Bajocian to Bathonian). The Rimthan and Qatar Arches, which acted as barriers to restrict the Arabian intrashelf basin, are highlighted in red rectangles (After Ziegler, 2001).

CHAPTER 3

METHODOLOGY

The focal point of this study is to define a high frequency sequence stratigraphic framework for the Lower Fadhili reservoir in Khurais complex based on core studies to indentify the sedimentology and utilize borehole gamma-ray logs. Nine wells with continuous cored interval through the Lower Fadhili reservoir were selected for this study. The methodologies for this study were divided into two categories: geological core description and sequence stratigraphic interpretation. The methodologies are as follows:

1. **Geological Core Description**

   a. **Core description:** The core descriptions were acquired at the core lab facilities of Saudi Aramco by using a hand lens, binocular microscope, and core description sheets. Core description sheets, designed specifically for carbonate reservoirs and developed in Saudi Aramco (Figure 3.1), were used to display detailed, bed-by-bed, sedimentological description of the core. The scale of the core description sheets were 1:120 (1 inch =10 ft). The sedimentological data that were described and are displayed in the core description sheet are:

      i. Stylolites and fractures

ii. Percentage of pore type

iii. Percentage of mineralogy composition and visible porosity

iv. Sedimentary structures including: argillaceous micro stylolites, burrows, cross beds, hardgrounds and firmgrounds.

v. Carbonate texture (modified Dunham, 1962)

vi. Grain type (skeletal and non-skeletal grains)

vii. Bed boundaries

viii. Grain size

ix. Fossil contents

x. Cyclicity

b. **Core-to-log Calibration**: core descriptions were calibrated with their borehole wireline-logs (e.g., gamma-ray logs) and they were matched together. Shale minerals show high gamma-ray values and limestone minerals show relatively low gamma-ray values. According to this technique, the core descriptions were matched with their borehole wireline gamma-ray logs.

c. Lithofacies identification: Lower Fadhili carbonate facies were defined for each core based on sedimentary characteristic sets (e.g., texture, fossil content, lithology, color and structure) (Tucker, 1990).

2. **Sequence stratigraphic interpretation**

a. Build a conceptual depositional model: depositional processes and depositional settings for each identified facies were interpreted and have been integrated into a 2D depositional model.

b. **Parasequence identification:** parasequences were identified by using sedimentologic characteristics, such as, major surfaces, sedimentary structures, rock types, particle types, and their vertical facies changes.

c. **Parasequences correlation:** 2D sequence stratigraphic framework was constructed by correlating parasequences from one cored well to the next cored well by using the gamma-ray character of the open-hole log and the core description. During the parasequences correlation the following concerns have been considered: parasequences are diachronous units, with parasequence boundaries and sequence boundaries time lines. The depositional model was utilizing as a guideline for facies distribution and correlation.

d. **Systems Tracts and Maximum Flooding Surface identification:** a stacking pattern of individual parasequences, parasequence sets and their vertical succession were identified. The vertical changes of the facies in the parasequence sets were identified together with considering the relationship between the amount of accommodation space available and the rate of sedimentation. All those were considered in identifying the systems tracts.

e. **Identify the good reservoir facies:** by utilizing the sequence stratigraphic framework, the distribution of the good reservoir facies were identified vertically and laterally and placed into a predictive framework.

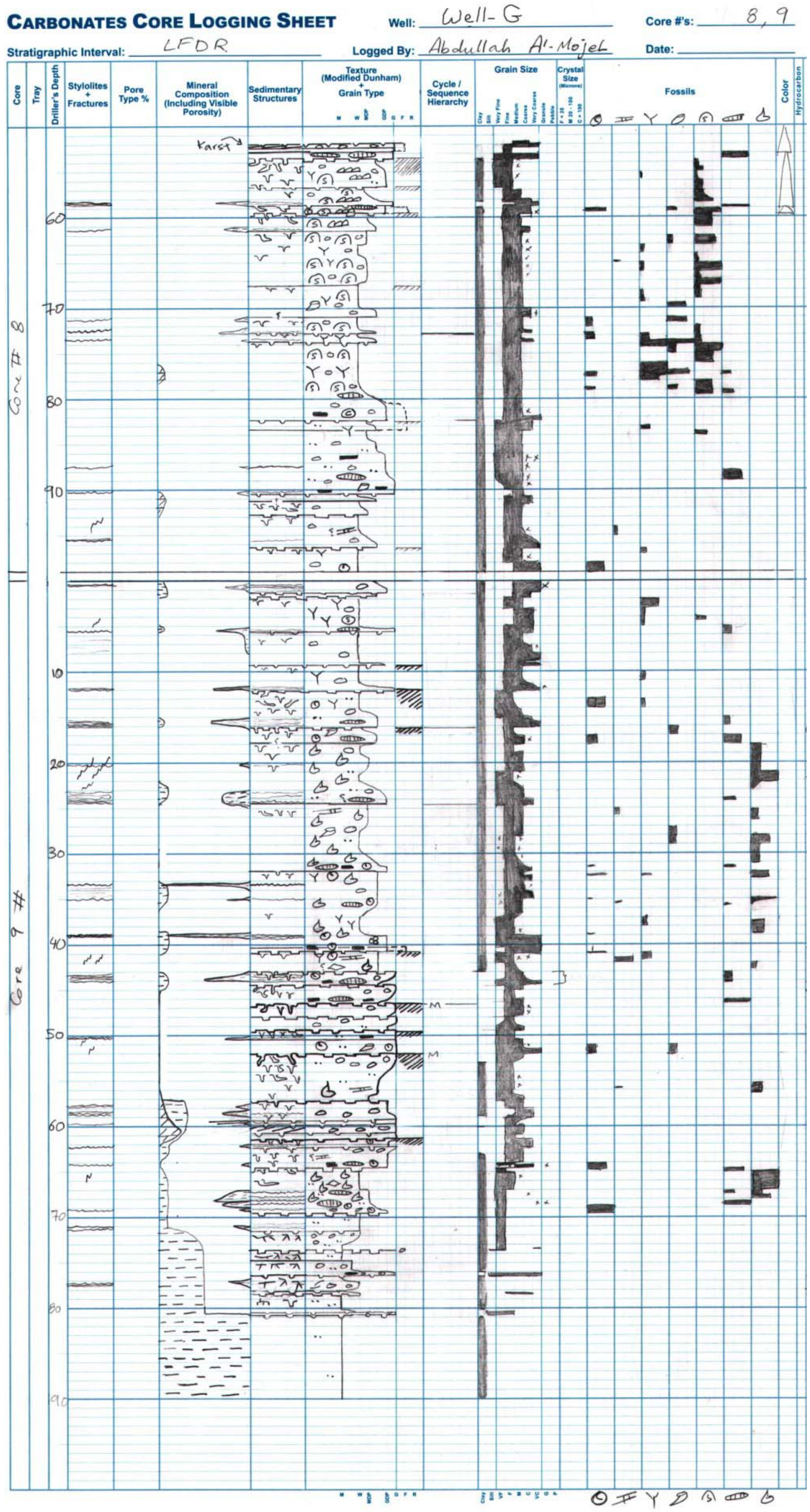


Figure 3.1. Example of a core description sheet. The core description is from Well-G in Mazalij area.

CHAPTER 4

LOWER FADHILI RESERVOIR LITHOFACIES AND DEPOSITIONAL ENVIRONMENT

4.1. LOWER FADHILI DEPOSITIONAL MODEL

Lithofacies is a subunit of a stratigraphic succession which is characterized by a group of sedimentologic properties (e.g., rock constituent, sedimentary structure, depositional texture using the modified Dunham (1962) classification, and fossils content). In this study the name of grain and fossil types of each facies are listed in reverse order of abundance, such as ooid peloid grainstone would consist mainly of peloids. Each facies refers to a specific depositional environment, which has been interpreted based on the sedimentologic description.

Lithofacies, cycles, and additional orders of sequence stratigraphy of the Lower Fadhili reservoir in Khurais complex have been identified for a shallow carbonate ramp which gently dips toward the north and east of Khurais complex. Ahr (1973), Read (1985), and Burchette and Wright (1992) defined the carbonate ramp as a gentle dipping depositional surface of < 1°, with no increase or break in slope. The prevailing depositional setting for the Lower Fadhili Reservoir in the Khurais complex was shallow-marine lagoon setting. This suggests that on the large scale the depositional environment of the Lower Fadhili reservoir in Arabian basin was bounded by the Qatar Arch to the east and the Rimthan Arch to the north, which acted as barriers (Figure 2.3).

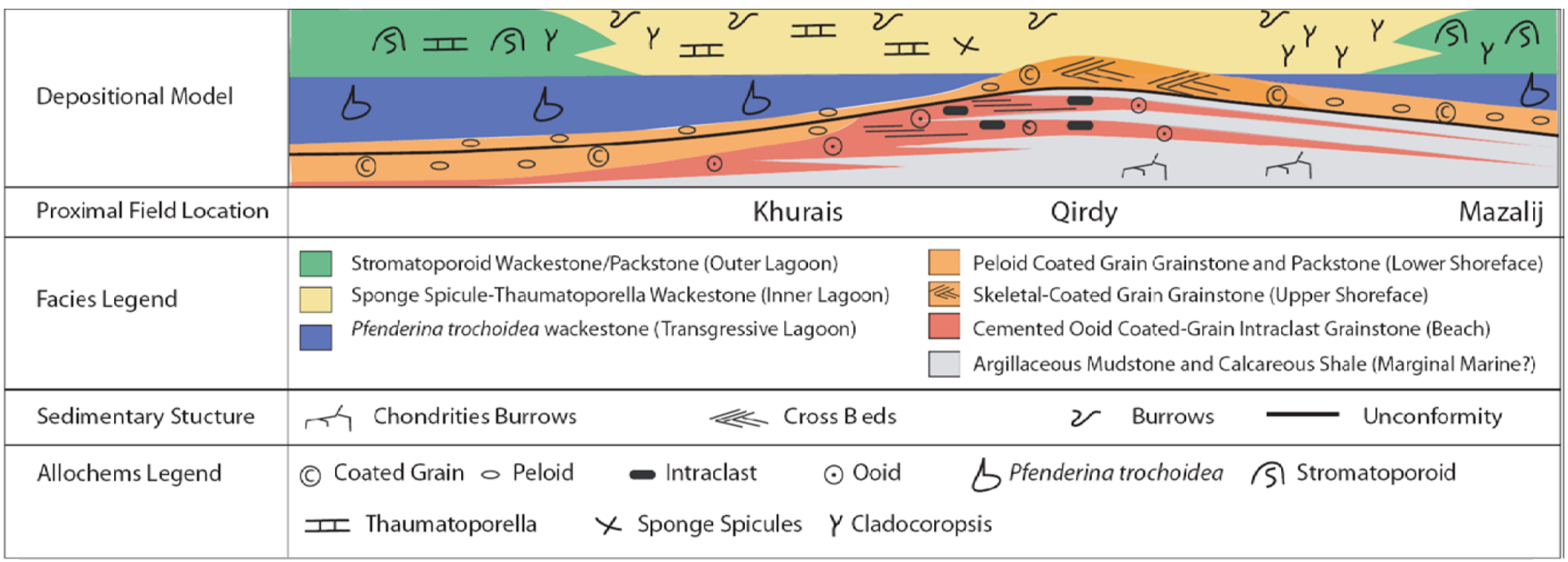


Figure 4.1. Lower Fadhili reservoir ramp model within which the full spectrum of Lower Fadhili facies are organized from proximal to distal facies. The black line reflects the initial depositional surface of Khurais, Qirdy and Mazalij.

4.2. LOWER FADHILI RESERVOIR FACIES AND DEPOSITIONAL ENVIRONMENT

The Lower Fadhili depositional environment contained the following facies:

4.2.1. ARGILLACEOUS MUDSTONE AND CALCAREOUS SHALE (MARGINAL MARINE)

This facies association consists of gray to dark-green, calcareous fissile shale, and gray to olive green argillaceous lime mudstone. The argillaceous lime mudstone units are typically 0.5 meter to 1.0 meter thick and have abundant chondrites burrows, with common gastropods, oyster-like bivalves and echinoderms. The individual beds of the calcareous fissile shale are between 0.3 meters to 2.7 meters thick. This facies association occurs above and below the Lower Fadhili carbonates and is easy to map using wire-line logs with the gamma ray higher in such shaly intervals. The shales also have a wide spread between the density and neutron porosity log with the neutron showing more porosity. The shales have hydrogen ions in the clays, which cause the neutron porosity log to read higher porosity. This facies is commonly interbedded with ooid grainstone at the base and top of the Lower Fadhili.

This facies is here interpreted to be marginal to shallow marine, landward of the carbonate beach facies. The clay was likely sourced from the Arabian shield to west. Ziegler (2001) identified a belt of siliciclastics that were deposited along the edge of the Arabian Shield and widespread occurrences of clay at Khurais and Mazalij likely indicate significant regressions of the shoreline. It is interbedded with cemented ooid grainstone which typically forms in very shallow high-energy marine water within wave base. Wave base was in < 10 m water depth. The argillaceous mudstones were deposited below wave base. The marl is interpreted to be formed in the hinterland.

4.2.2. CEMENTED OOID COATED-GRAIN INTRACLAST GRAINSTONE (BEACH)

This facies consists of dark gray to light gray, low angle cross-bedded, well sorted, fine-grained grainstone containing broken ooid, intraclast, coated-peloid, and occasionally laminated grainstone. The facies has low diversity with skeletal debris primarily consisting of bivalves and gastropods. This facies occurs in beds from a few centimeters thick to as much as 3.3 meters thick. This facies is deposited only at the base of the lowermost sequence and is capped by an exposure surface that is marked by a well-developed hardground. Below the unconformity, dissolution features (e.g., some of the grains are partially and/or totally dissolved) and meteoric cement (phreatic and vadose) were observed in the thin section. In addition, this facies is cemented by early ferroan calcite cement followed by non-ferroan calcite cement with no apparent compaction. Early cementation prior to compaction would imply that this facies formed beach rock.

This facies is interpreted to have formed on a beach to upper foreshore setting. The beach rock was deposited in high-energy wave base. The beach facies is thickest on structural highs in the Qirdi area.

Core Sample								
Color Code								
Facies	Argillaceous Mudstone and Calcareous Shale	Cemented Ooid Coated-Grain Intraclast Grainstone	Cemented Ooid Coated-Grain Intraclast Grainstone	Skeletal Coated-Grain Grainstone	Peloid Coated-Grain Grainstone and Packstone	Thaumatoporella Wackestone	Stromatoporoid Wackestone/Packstone	*Pfenderina Trochoidea* Wackestone/Mudstone
Depositional Environment	Marginal marine	Beach ridge	Beach	Uppershoreface	Lower shoreface	Inner Lagoon	Outer Lagoon	Transgressive Lagoon
Rock Type (Dunham)	Mudstone	Grainstone	Grainstone	Grainstone	Grainstone	Wackstone	Packstone and Wackstone	Wackstone
Mineralogy	Calcareous fissile shale/ Argilaceous Lime mudstone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone
Grain Type	Peloids, pellets	Ooids, peloids, pellets, Bivalves and Gastropods.	Intraclasts, coated grains, ooids, peloids	Coated grains,, oids, skeletal fragments, peloids	Oncoids, coated grains, peloids	Peloid and Thaumatoporella	Peloids, Stromatoporoid and Cladocoropsis	Peloids and *Pfenderina trochoidea*
Fossils	Thin-shelled bivalves	Gastropod, Bivalve	Milliolid	Echinoderms, Brachiobods	Echinoderms, Brachiobods	Thaumatoporella	Cladocoropsis, Stromatoporoid	*Pfenderina trochoidea*
Sedimentary Structure	Chondrities burrows, firm and hardground	laminated to structureless & burrows	Low-angle crossbeds	Low-angle to high-angle crossbeds	Burrows capped by hardground	Burrows capped by firmgrounds	Firm and hardground	Firm and hardground
Grain size	Clay-Silt	Fine-Medium	Fine	Medium - Coarse	Medium-Coarse	Very fine-Medium	Fine-Coarse	Very fine-Medium
Color	Olive green	Dark and light gray	Black and light gray	light gray (locally reddened)	Dark gray and tan	Tan	Tan	Tan
Reservoir Quality	None	None	None	None	High Interpartical porosity and high Permeability	High microporosity, low permeability	Microporosity, intraskeletal and low interpartical porosity, fair permeability	High microporosity, low permeability
Diagenetic Elements	None	Early ferroan calcite cement, no compaction	Cemented with (vadose and phreatic)meteoric calcite cement - early ferroan calcite followed by non-ferroan calcite - no compaction.	Cemented with (vadose and phreatic) meteoric calcite cement - early ferroan calcite followed by non-ferroan calcite - no compaction.	Cemented with early Isopaceous marine cement, partially cemented with late saddle dolomite, low compaction	Minor saddle Dolomite cement	Minor saddle Dolomite cement	Minor saddle Dolomite cement

Table 4.1.Summary of the Lower Fadhili Carbonates facies.

4.2.3. SKELETAL COATED-GRAIN GRAINSTONE (UPPER SHOREFACE)

This facies consists of light gray, high-angle cross bedded grainstone (Figure. 4.5). Grain size is generally medium- to coarse-grained grainstone and bed thickness ranges from 0.3 to 3.3 meters. Common grain types include fossil debris, rare ooids, peloids, and coated peloids. This facies differs from the cemented ooid coated-grain intraclast grainstone facies in that it is porous, coarser, contains greater faunal diversity, high-angle cross bedding, and was sparingly cemented with marine cement and early light-ferroan calcite cement followed by non-ferroan calcite cement. This facies contains fossils such as echinoderms, coral, and gastropod.

The high-angle cross bedding grainstone formed in upper wave base at the upper shoreface. The high-angle cross bedding suggest that the water depth was slightly shallower in the upper part of wave base than in case of the structureless coated grain grainstone/packstone facies that most likely formed in the lower part of wave base.

4.2.4. PELOID COATED-GRAIN GRAINSTONE AND PACKSTONE (LOWER SHOREFACE)

This facies consists of dark gray to tan, structureless, medium- to coarse-grained grainstone and packstone. Grain types include oncoids, coated-grains, peloids, and was partially cemented with early marine isopachous cement and late saddle dolomite cement. These can form in beds from 0.15 to 3.6 meters thick. These facies are deposited mainly in the first sequence and overlie hardground and firmground surfaces. This facies contains fossils including echinoderms, coral and gastropod.

These grainstones were deposited in shallow, high-energy marine water, and interpreted to have been deposited in a lower shoreface environment. This facies formed within fair-weather wave base.

The lower shoreface facies contains the best reservoir quality in the lower Fadhili reservoir of Khurais field. Because of the lack of cementation, this facies contains well connected interparticle porosity and high permeability relative to other facies.

4.2.5. *THAUMATOPORELLA* WACKESTONE (INNER LAGOON)

This facies is tan, bioturbated, and capped by a hardground and/or firmground. It contains very-fine to medium-grained wackestone composed of peloids, pellets, and fossils. *Thaumatoporella* is the most common and abundant biota in these facies. This facies forms beds that are 0.3 to 2.4 meters thick.

This facies is interpreted to have been deposited in a shallow-marine quiet lagoonal setting and protected by a seaward stromatoporoid facies. The *Thaumatoporella* wackestone facies formed immediately beneath fair-weather wave base in the inner lagoonal setting.

Figure 4.2. Core photographs of the dark-green, unfossiliferous calcareous fissile shale.

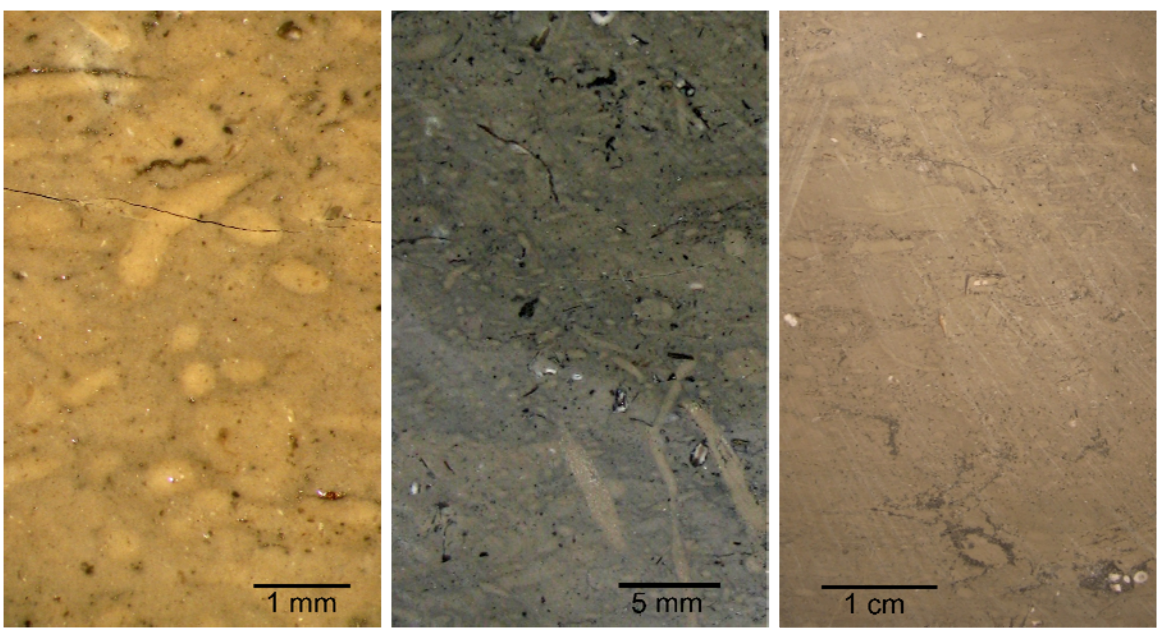


Figure 4.3. Core photographs of the marginal marine facies. The core shows Chondrites burrows.

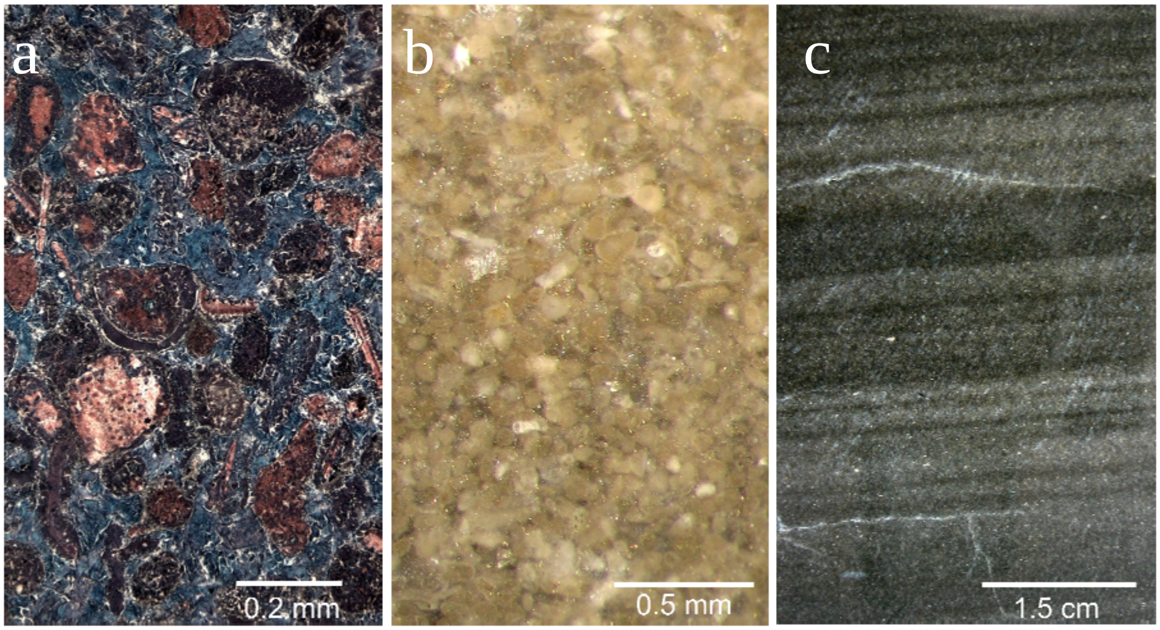


Figure 4.4. Core photographs of the beach facies. (a) Thin section view of beach facies showing ferroan calcite cement in blue color and broken ooid in the middle, plane polarized light and stained with Alizarin Red S. (b) Binocular microscope view showing coated-grain. (c) Slabbed core hand sample showing low angle cross bedding.

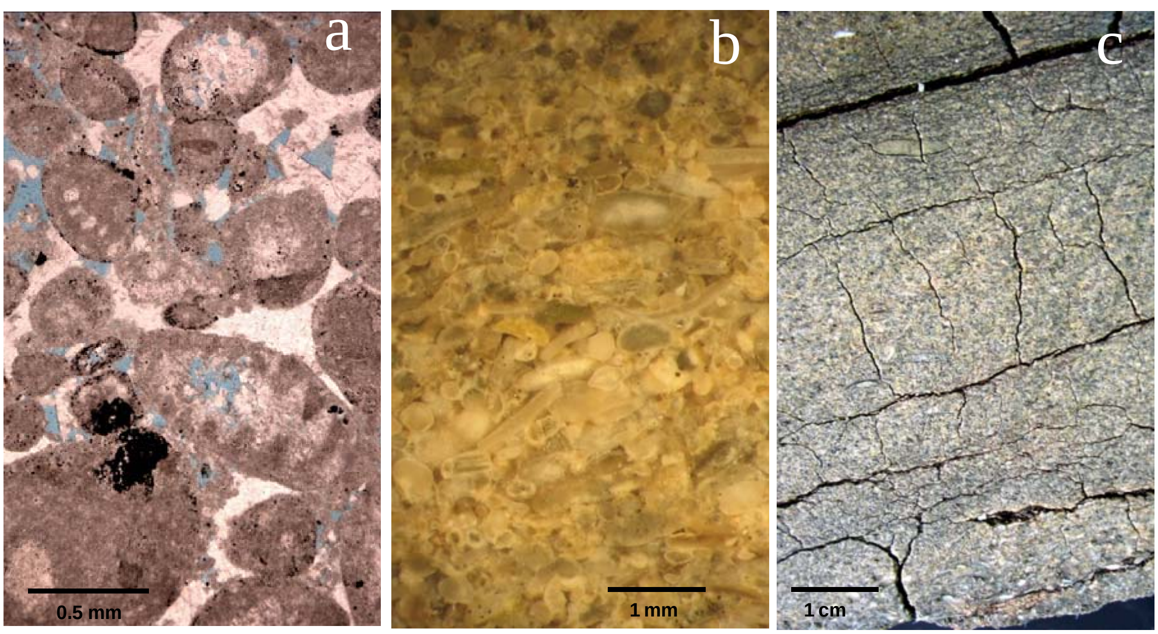


Figure 4.5. Core photographs of the upper shoreface facies. (a) Thin section showing early blocky calcite cement and porosity in light blue color, plane polarized light and stained section with Alizarin Red S. (b) Binocular microscope view showing skeletal fragments, coated grain, ooid and peloid. (c) Slabbed core hand sample showing coarse grain and high angle cross bed structure.

4.2.6. STROMATOPOROID WACKESTONE/PACKSTONE (OUTER LAGOON)

These are tan, structureless, and fine- to very coarse-grained peloid stromatoporoid packstone and peloid domal and encrusting stromatoporoids and Cladocoropsis wackestone. These facies are generally 0.45 to 3 meters thick, and are composed of domal and encrusting stromatoporoid, *Cladocoropsis* and rare tabulate corals with less common sponge spicules and *Thaumatoporella*.

The stromatoporoids are typically small fragments that are not buildups (Figure 4.8) suggesting that the depositional setting of the stromatoporoid is storm reworked mounds and not an in-place reef. This facies is relatively grainy compared to the up-dip *Thaumatoporella* wackestone facies. That means that the stromatoporoid facies is with the lower part of fair-weather wave base.

4.2.7. *PFENDERINA TROCHOIDEA* WACKESTONE/MUDSTONE (TRANSGRESSIVE LAGOON)

This facies is not bioturbated and consists of tan, structureless, very fine to fine grained, pellets, peloids wackestone/mudstone. *Pfenderina trochoidea* (Figure 4.10) is the most common and abundant foraminifera in this facies. *Thaumatoporella*, sponge spicules and *Cladocoropsis* are common but less abundant in this facies and there are rare stromatoporoids. This facies occurs in beds that are 0.3 to 2.2 meters thick, exists only in the lower part of the Lower Fadhili reservoir and commonly overlies the coated-grain grainstone and packstone. This facies is capped by hardgrounds and/or firmgrounds.

The facies is deposited in low-energy shallow-marine lagoonal setting below and/or behind fair-weather wave base. The facies thins toward the crest of the Khurais and the Qirdi structure and thickens off the structure. The facies occurs only in the transgressive systems tract of the first cycle, representing the most distal facies.

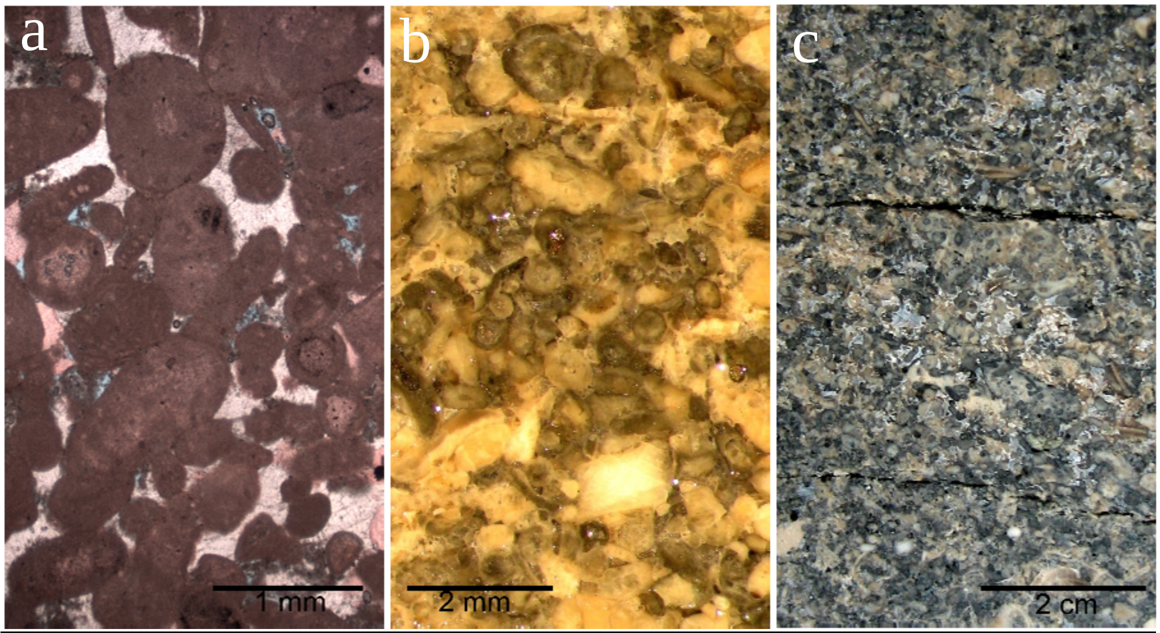


Figure 4.6. Core photographs of the lower shoreface facies. (a) Thin section showing saddle dolomite cement, porosity in light blue color, and coated grains; plane polarized light stained with Alizarin Red S. (b) Binocular microscope view showing coated-grains. (c) Slabbed core hand sample showing coated-grains, peloids, and saddle dolomite.

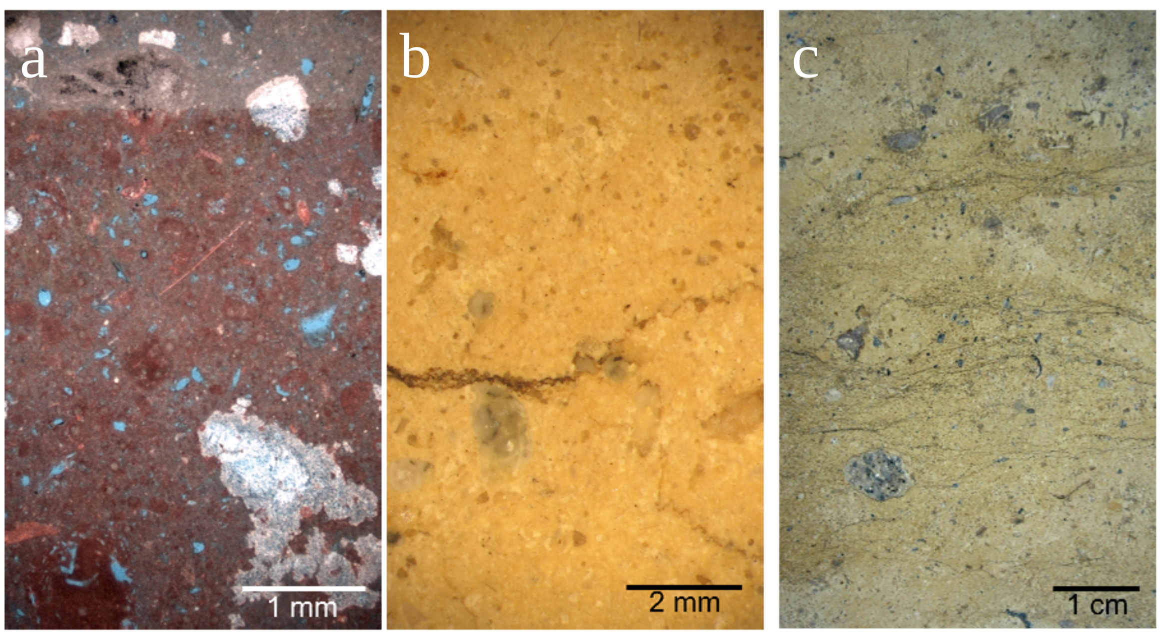


Figure 4.7. Core photographs of the *Thaumatoporella* wackestone. (a) Thin section showing saddle dolomite cement, and porosity in light blue color. The view is in plane polarized light and the thin section is stained with Alizarin Red S. (b) Binocular microscope view showing peloid (gray grain) and lime mud (tan matrix). (c) Slabbed core hand sample showing peloids and lime mud.

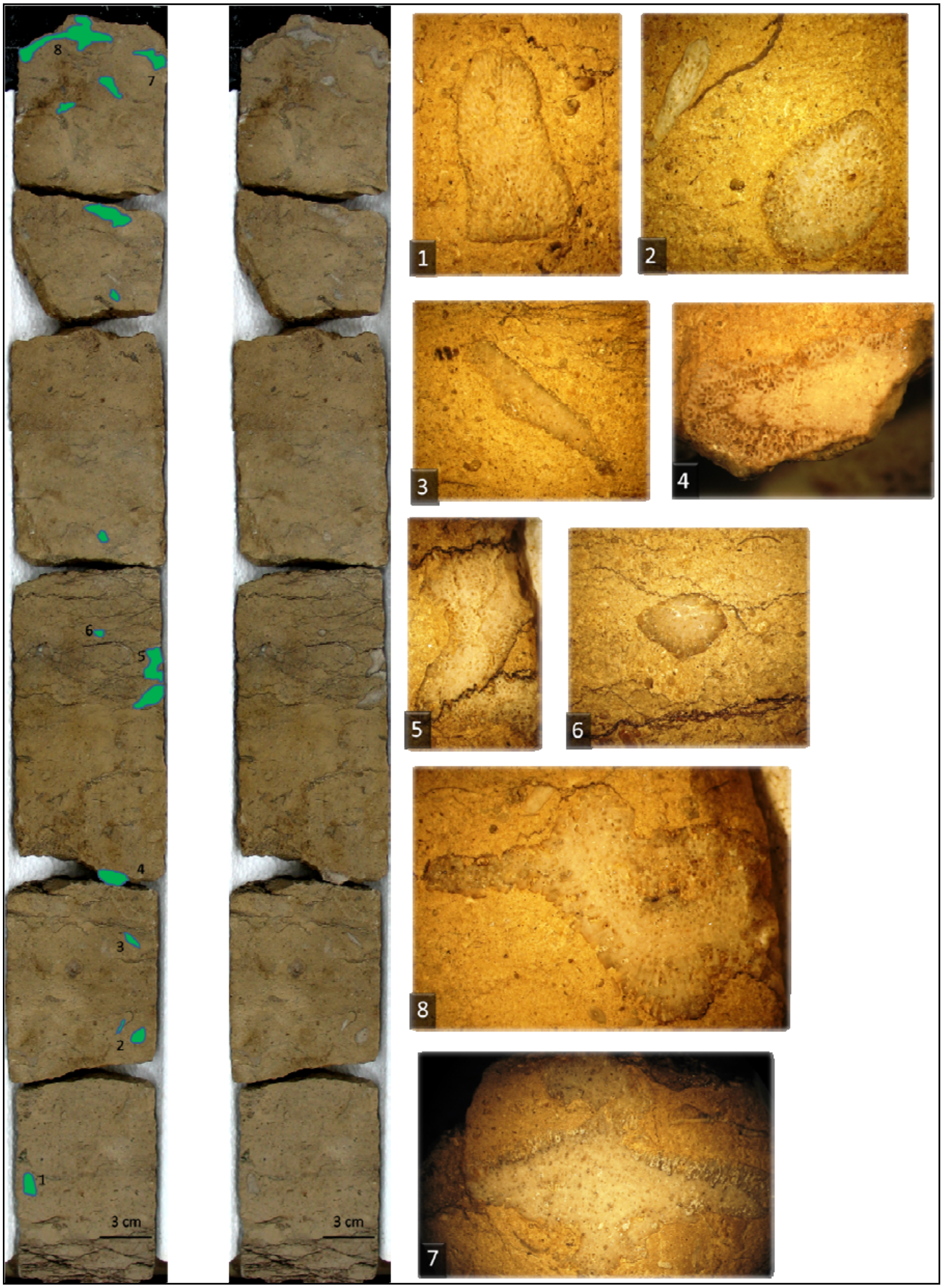


Figure 4.8. Core photographs of the stromatoporoid facies showing the general morphology of the stromatoporoid species in the Lower Fadhili.

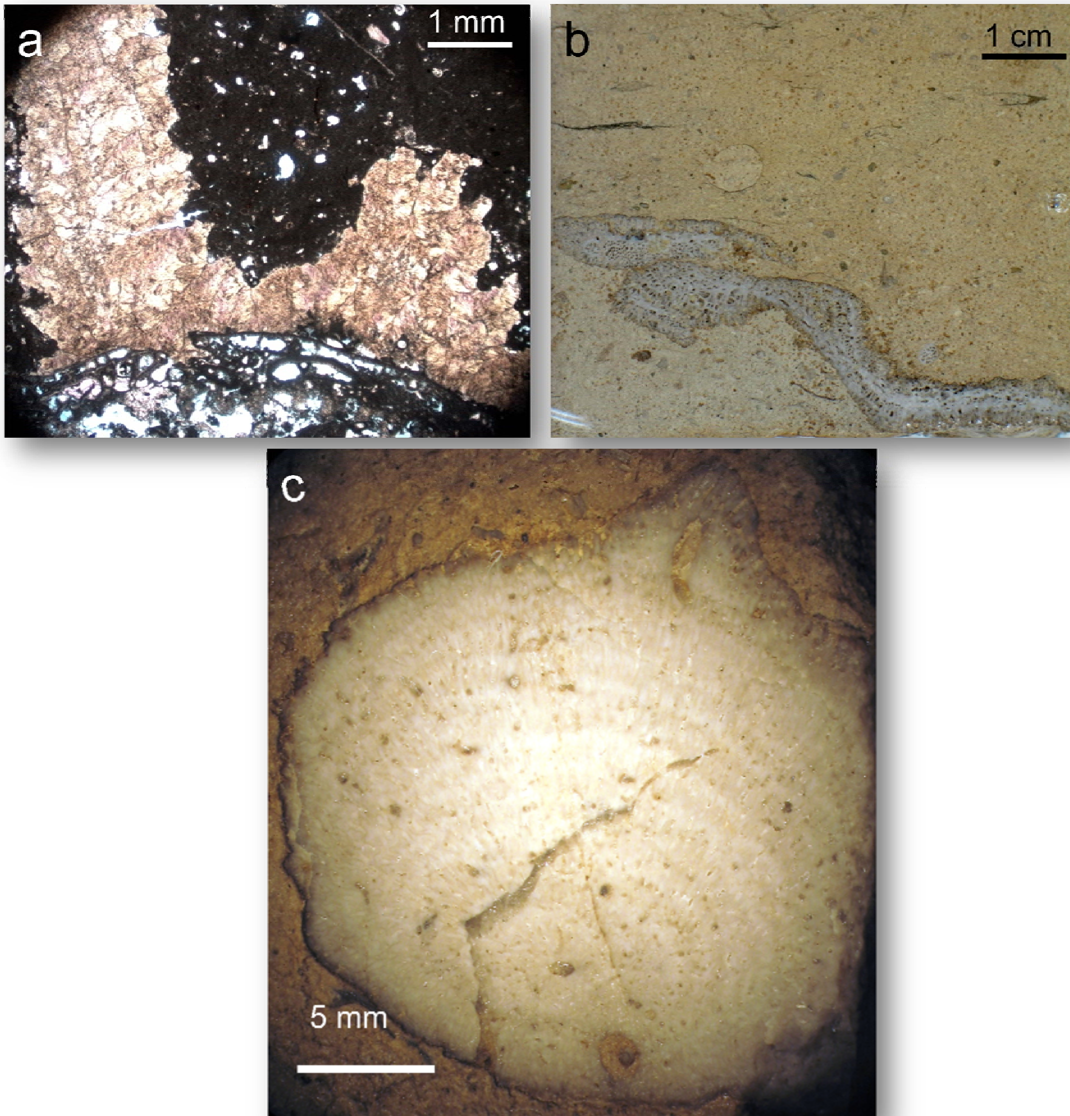


Figure 4.9. Core photographs of the stromatoporoid facies showing two morphology type for the stromatoporoid species. (a) Thin section view showing encrusting stromatoporoid, plane polarized and stained with Alizarin Red S. (b) Encrusting stromatoporoid in hand sample. (c) Binocular microscope view showing domal stromatoporoid.

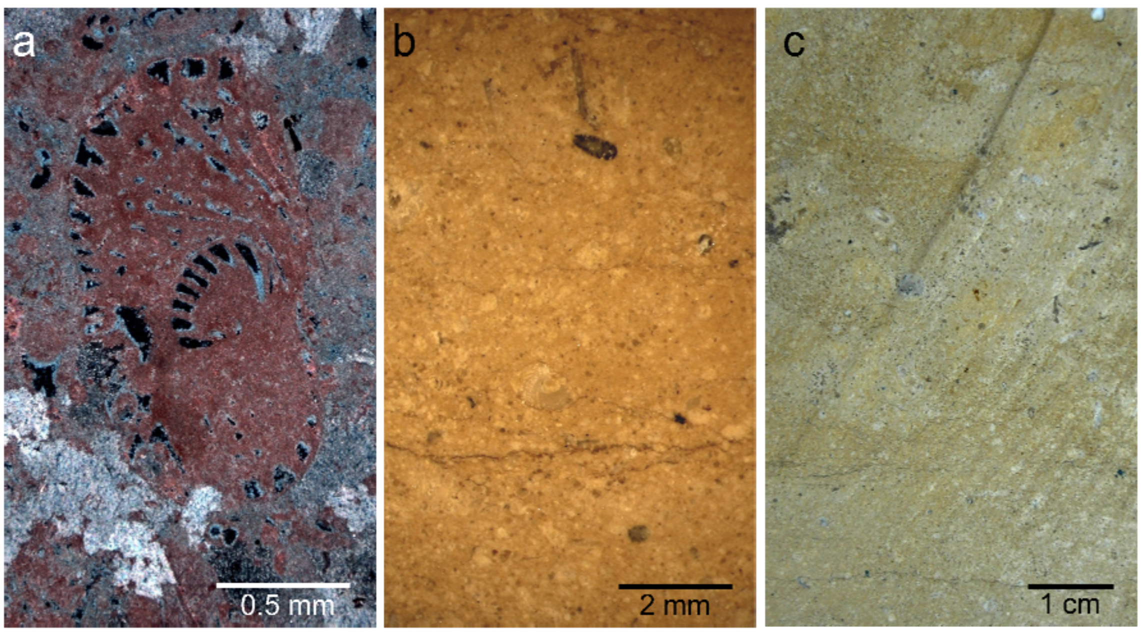


Figure 4.10. Core photographs of the *Pfenderina trochoidea* wackestone facies. (a) Thin section view showing *Pfenderina trochoidea*, crossed polarized light and stained with Alizarin Red S. (b) Binocular microscope view showing *Pfenderina trochoidea* in the middle and lime mud (tan matrix). (c) Slabbed core hand sample.

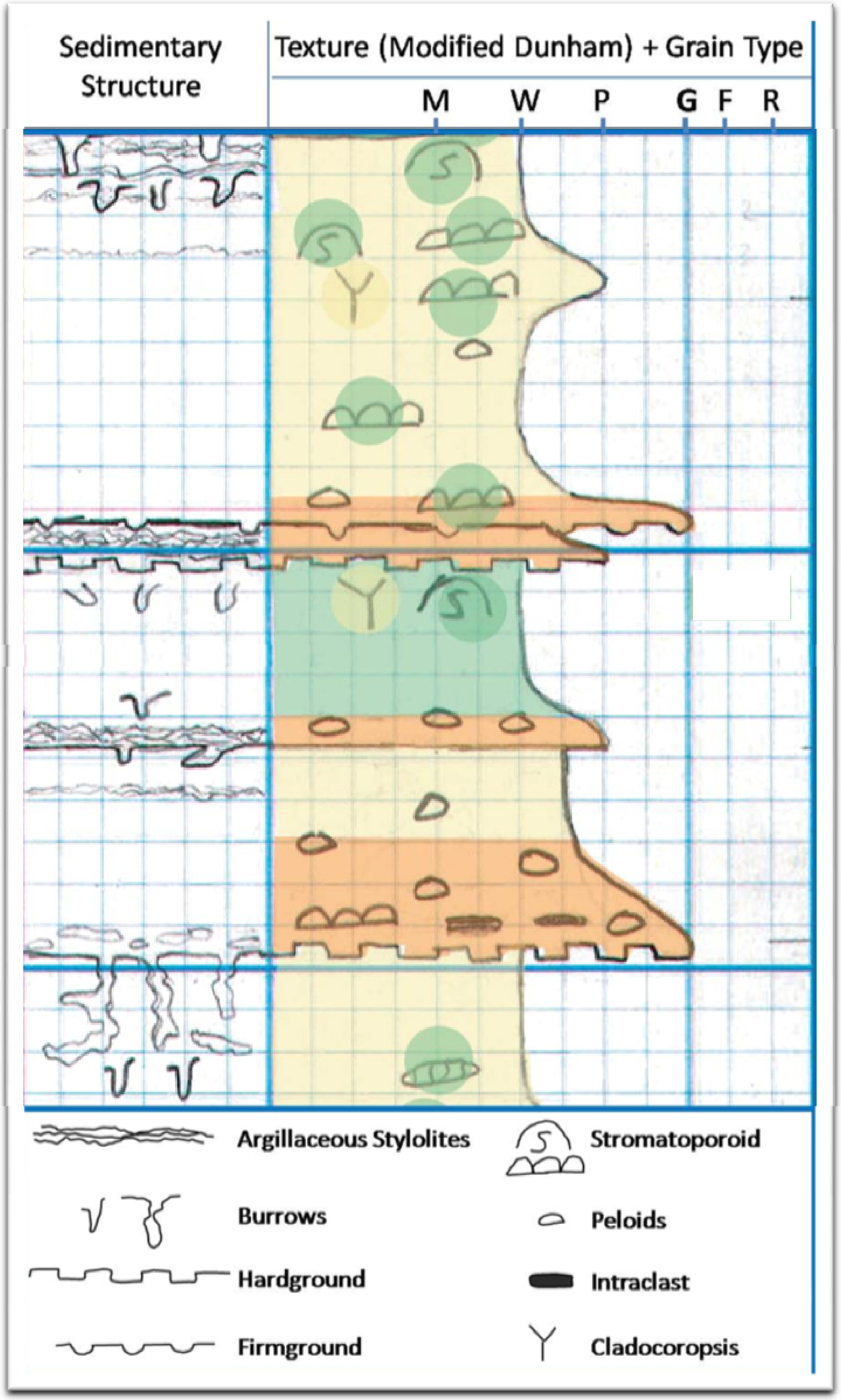


Figure 4.11. Part of the core description and legend of Well-C showing the transgressive sediments composed of peloid coated-grain grainstone/packstone facies in orange color, stromatoporoid facies in green color, and Thaumatoporella wackestone facies in tan color. The transgressive facies are clearly deepening- and fining-upwards which are capped by hardground/firmground surfaces. M = Mudstone, W = Wackestone, P = Packstone, G = Grainstone, F = Floatstone, and R = Rudstone.

4.3. FACIES DISCUSSION

The facies that have been discussed partitioned into cycles, cycle sets, and high-frequency sequences. Firmgrounds and hardgrounds are here thought to be transgressive surfaces of erosion (TSE). Firmgrounds and hardgrounds have been burrowed and bored by trace fossils into underlying facies. The burrows and borings are filled by the overlying, transgressive sediments which are typically coarser and grainier (Caron et al., 2004). Coated-grain peloid grainstone/grain dominated packstone in the base of the sequence is representing the transegressive sediment that backstepped and deepened and that fined upward (Figure. 4.11).

Stromatoporoids are strongly related to the sea chemistry. In the geological time, they mainly exist in two periods in the Devonian (Paleozoic) and Middle Jurassic - Cretaceous (Mesozoic). In these two periods sea water was saturated with calcite and referred to as a calcite sea. Aragonite was associated with hypersaline lagoon Wilkinson et al., 1985). Most stromatoporoids are composed primarily of calcite except some groups that were aragonitic (Scholle P., 2003). The favored conditions for Mesozoic stromatoporoids to have lived in were within the lower part of high-energy wave base that was bathed with open marine circulation. In addition, stromatoporoids have been noticed to be absent in elevated salinity depositional setting such as the Arab-C, B, and A. (Toland C., 1994).

Thaumatoporella is a green algae (according to, Flügel, 2004). Green algae need much higher light for photosynthesis (website of The Western Australian Museum). The abundance of the green algae indicates a shallow water depositional environment behind fair-weather wave base, probable back reef lagoonal setting (Souissi et al., 2009). This suggests that the depositional setting of the *Thaumatoporella* is more proximal to the shoreline than the stromatoporoids facies.

Cladocoropsis populated inter mound to back reef lagoonal setting (Toland C., 1994). Outcrop work in the Tuwaiq Mountain Formation has shown Shuqraia the older equivalent of *Cladocoropsis* to have populated in for mound areas (Lindsay, 2010, personal communication). *Cladocoropsis* preferred sheltered and protected areas away from high-energy. In the Lower Fadhili depositional model, the *Cladocoropsis* is located between the *Thaumatoporella* and the stromatoporoid facies and may be a transitional facies between the *Thaumatoporella* and the stromatoporoid facies. This same depositional setting has been noted for the Arab-D reservoir in Ghawar field (Lindsay et al. 2006).

The *Pfenderina trochoidea* wackestone also appear to be common in the transegressive parts of the sequence where they appear to fill topographic lows in the lower sequence and are associated with mud-rich lithofacies in the Lower Fadhili reservoir. Hughes (2004) interpreted *Pfenderina trochoidea* to be one of the deep lagoon biofacies in the Lower Fadhili reservoir.

The cemented ooid coated-grain intraclast grainstone has most of the sedimentology characteristics of beach facies. Examples for the beach sedimentology characteristics are parallel-laminated grainstone with seaward dip of low angle bedding and evidence for subaerial diagenetic processes (e.g., karstification and meteoric cementation). The type of diagenetic processes depends on climate (Tucker, 1990).

The argillaceous mudstone and calcareous shale facies are interpreted to be genetically related to the cemented ooid coated-grain intraclast grainstone facies because the two facies are interbedded together. Moreover, interbedding of these facies suggests a close depositional setting for them. The interbedding is clearly presented in the lower part of Well-C (Figure. 6.2, in Chapter 6) and in many other wells (Well-D and G). Therefore, the depositional setting of the argillaceous mudstone and calcareous shale facies is interpreted to be a back barrier of the beach facies in a marginal marine setting.

CHAPTER 5

LOWER FADHILI RESERVOIR SEQUENCE STRATIGRAPHY

The Lower Fadhili reservoir consists of two composite sequences (Figure 5.1), which in ascending stratigraphic order are: Lower Fadhili composite sequence 1 (LFC1); and Lower Fadhili composite sequence 2 (LFC2). Each composite sequence is composed of four high-frequency sequences (HFS). Each HFS of which is composed of multiple cycles and cycle sets. The base and the top of the Lower Fadhili reservoir are bounded by a subaerial exposure (karst) surface. The base lower Fadhili boundary, the base of LFC1, overlies a subaerial exposure (karst) surface on top of the ooid coated-grain intraclast grainstone beach facies that contains meteoric calcite cement, which is evidence for an exposure surface and a potential unconformity. The top Lower Fadhili reservoir (top of LFC2) is marked by a major subaerial exposure surface (karst), filled from the above by the green calcareous shale facies (reservoir seal) (Figure. 5.4).

Figure 5.1 shows the major cross-section for seven cored wells located in the crest of Khurais, Qirdy and Mazalij areas. The traverse of this cross-section is 119 km, and the seven wells are arranged from north-to-south as Well-A, Well-B, Well-C, Well-D, Well-E, Well-F and Well-G. The average well spacing is 19.8 km. Figure 5.2 is a second cross-section that contains three wells from Abu Jifan and Khurais area, with the cross-section oriented from southwest-to-east as Well-H, Well-C and Well-I. The second cross-section is 48 km in length. The two cross-sections cross each other at Well-C (Figure.

5.3). The data base for these cross sections was core descriptions (bed-by-bed) and the open-hole well logs gamma-ray (API 0-50).

The gamma-ray scale (API 0-50) is used to detect slight variations between the rock facies in the Lower Fadhili carbonate (Lucia, F. J., 1999). In general, the Lower Fadhili reservoir has low gamma-ray reading relatively to the overlain and underlain calcareous shale facies. Therefore the top and the base of the Lower Fadhili reservoir can be clearly defined correlated based on the gamma-ray log. The top sequence boundary of the Lower Fadhili reservoir shows peak high gamma-ray reading. The grainy facies, peloid coated-grain grainstone and packstone the best reservoir facies, in the Lower Fadhili reservoir have relatively high gamma-ray reading. The muddy facies, *Thaumatoporella* wackestone and *Pfenderina trochoidea* wackestone/mudstone, in the Lower Fadhili reservoir have relatively low gamma-ray reading. Therefore the gamma-ray logs have been used to correlate these facies between the wells. In addition, argillaceous stylolites in the Lower Fadhili reservoir show peak signatures in the gamma-ray log because the argillaceous stylolites contain insoluble residues. The argillaceous stylolites in the Lower Fadhili reservoir most of the time are associated with the grainy facies.

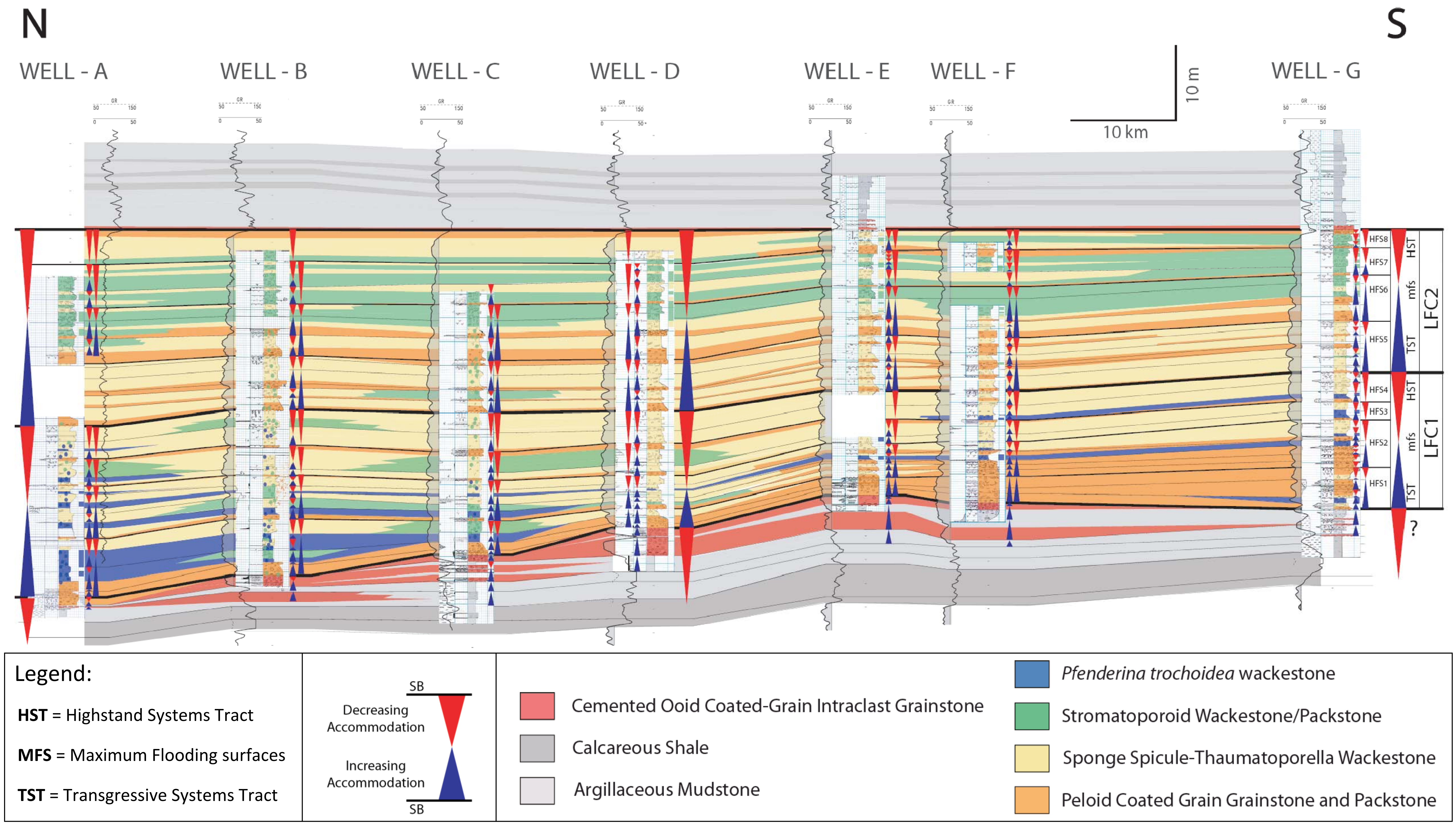


Figure 5.1 North-to-South cross section showing the interpreted sequence stratigraphic framework and facies distribution of the Lower Fadhili reservoir in the Khurais complex .

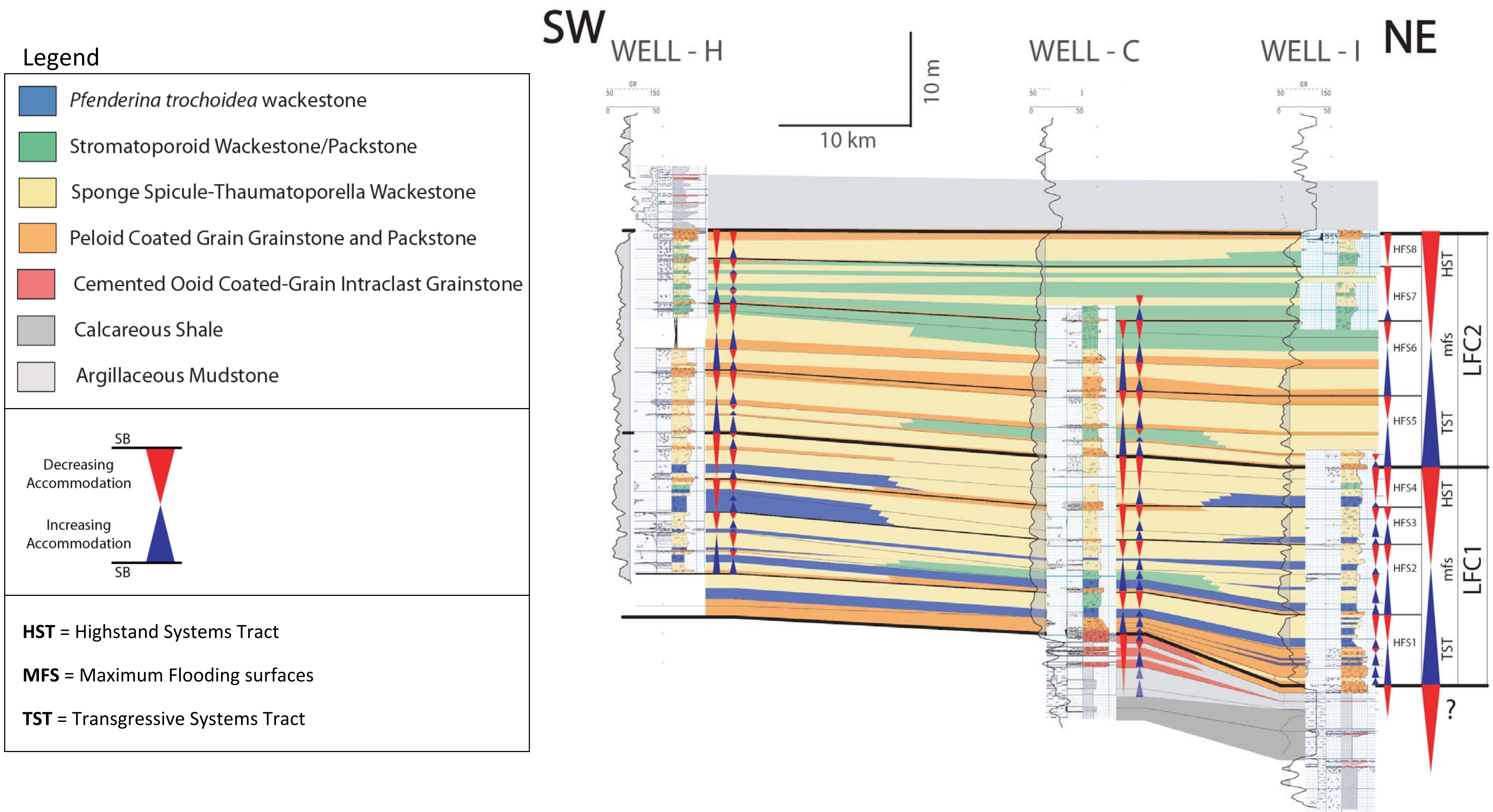


Figure 5.2. Southwest-to-Northeast cross section showing the interpreted sequence stratigraphy and facies distribution of the Lower Fadhili reservoir in the Khurais complex.

Khurais Complex

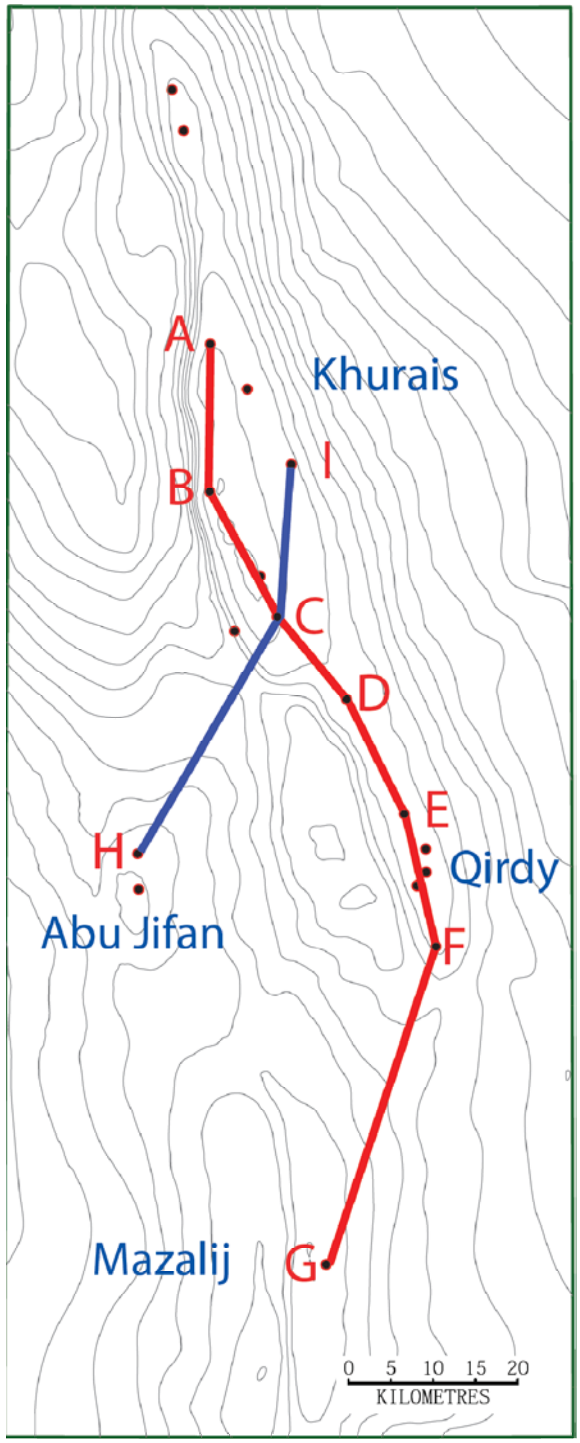


Figure 5.3 Index map of the Khurais complex showing field areas, well locations, and cross section traverses.

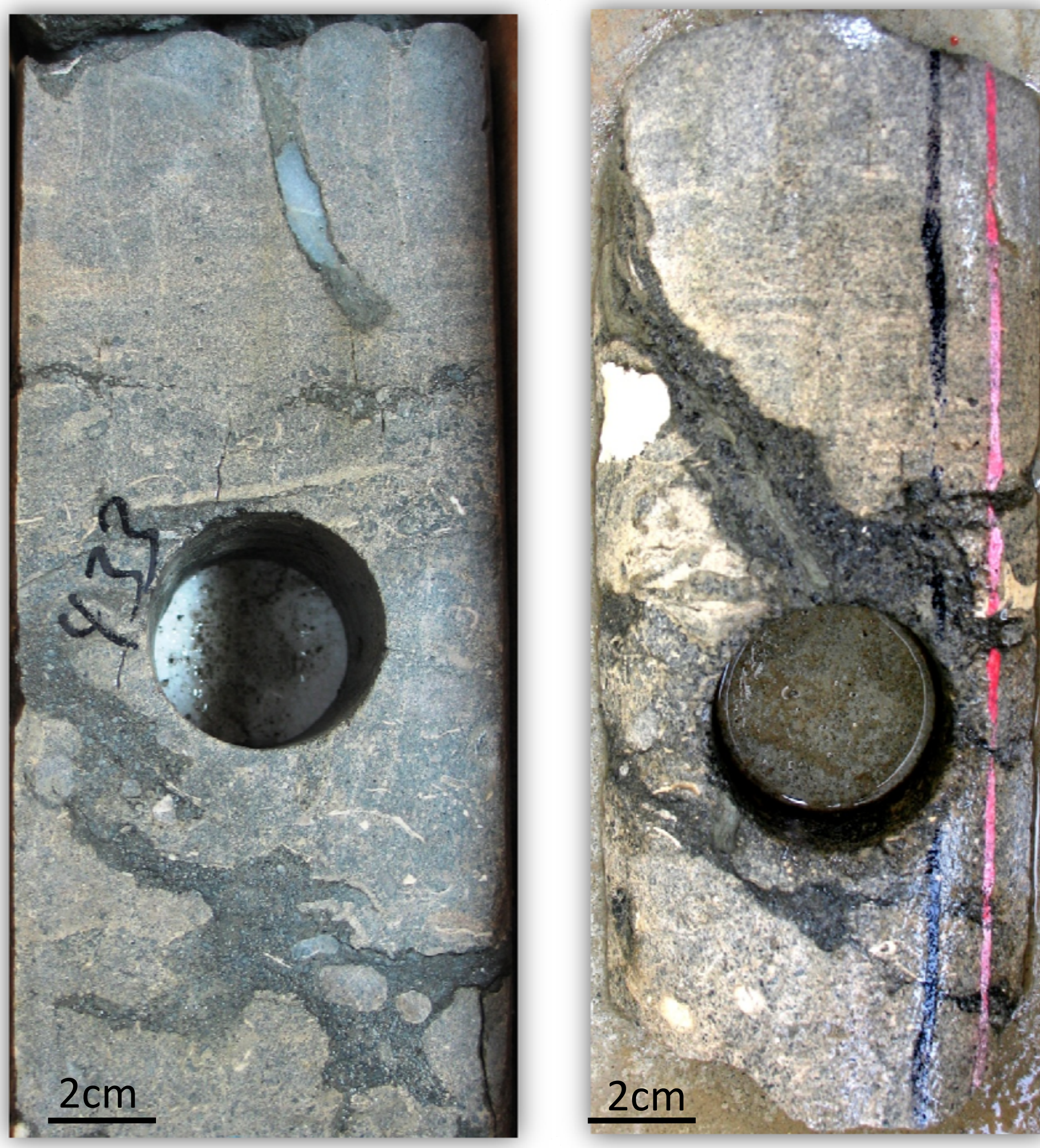
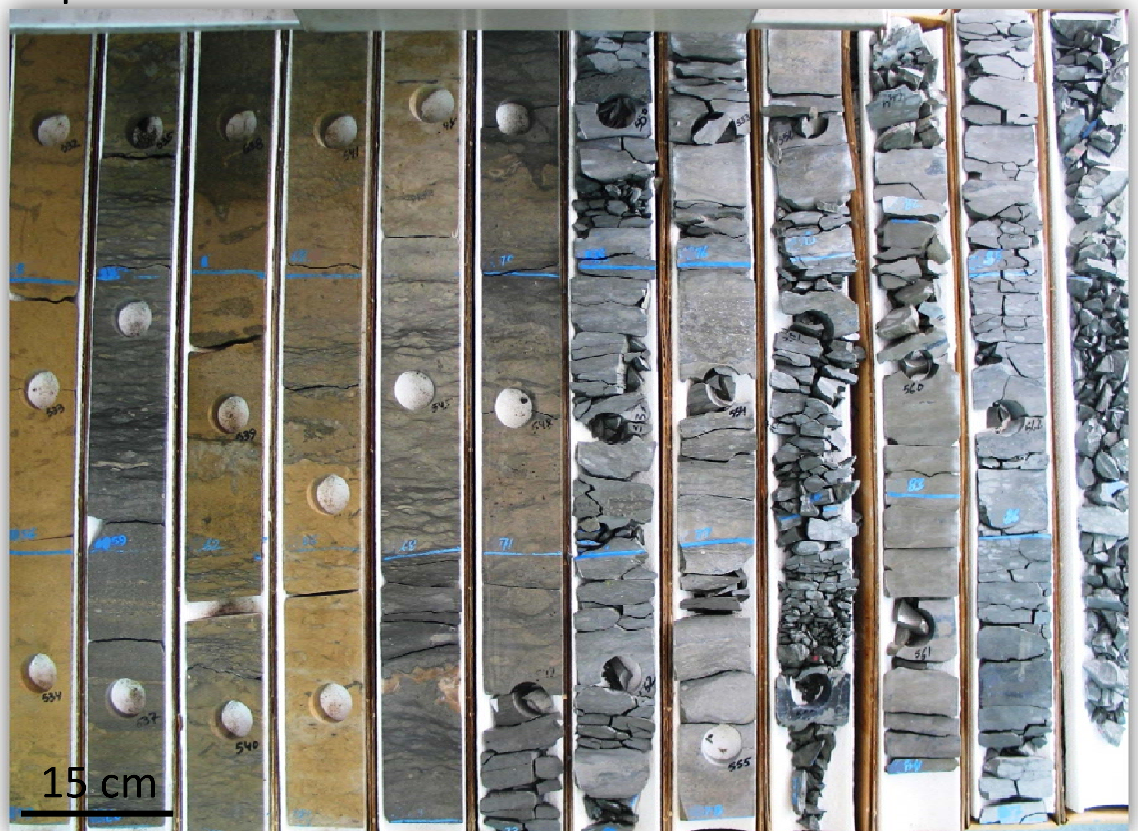


Figure 5.4. Core photos from the very top of the Lower Fadhili in Well-G showing leached hardground with green shale filling the voids beneath the surface. This is interpreted to be a karst surface marking a major sequence boundary at the top of LFC2. A similar surface occurs at the base of LFC1.

Top



Base

Figure 5.5. Core photo shows the calcareous fissile green shale below the basal sequence boundary of LFC1.

5.1. LOWER FADHILI COMPOSITE SEQUENCE 1 (LFC1)

Lower Fadhili composite sequence (LFC1) is thin in the Qirdy area, 13.5 meters (44.2 feet), and thickens toward the north and east to over 22.6 meters (74.1 feet). The LFC1 is defined at the base by the unconformity surface showing karstification features and meteoric cementations and from the top by a well developed hardground (Figure 5.6). The sequence consists of four upward-shallowing high-frequency sequences (from bottom-to-top): HFS1, HFS2, HFS3 and HFS4.

The early transgressive systems tract is marked by onlap termination of the first high-frequency sequences on the unconformity surface, the base boundary of this composite sequence. The remaining high-frequency sequences of the transgressive systems tract show a set of backstepping retrograding patterns of the *Pfenderina trochoidea* wackestone transgressive lagoon facies. The maximum flooding surface of LFC1 coincides with the maximum flooding surface of HFS2 and is defined by a thin layer of *Pfenderina trochoidea* wackestone transgressive lagoon facies. The high-stand systems tract is defined by stromatoporoid *Cladocoropsis* sponge spicules rich wackestone facies.

5.1.1. HIGH-FREQUENCY SEQUENCE 1 (HFS 1)

This high-frequency sequence, up to 2.3 to 7.8 meters (7.5-25 feet), is defined at the base by the karst surface cemented by meteoric cements. The transgressive Systems Tract of this high-frequency sequence is defined by coated-grain grainstone as transgressive shoreface. The sedimentary structure of this facies shows high angle cross bedded structures only in the Qirdy area (Well-E and F) (Enclosure 6.5 and 6.6). In addition, there are a lot of scouring surfaces in this facies especially in Well-E. The scouring surfaces are results of the surf-zone erosion in the shoreface setting (Tucker, 1990). The high angle cross bedded coated-grain grainstone shoreface facies are getting muddier toward the north and their sedimentary structure, high angle cross-bedding, starts to vanish toward the south. This suggests a paleotopographic high in Qirdy area especially in Well-E. The coated-grain grainstone shoreface is overlain by the *Pfenderina trochoidea* wackestone transgressive lagoon facies. The maximum flooding surfaces of this high-frequency sequence are picked on top the *Pfenderina trochoidea* wackestone transgressive lagoon facies. In the high-stand systems tract, the prevailing facies in the downdip area are *Thaumatoporella* wackestone facies and stromatoporoid wackestone/packstone, and their equivalent in the updip paleotopographic highs (Well-E, F and G) are ooid coated-grain grainstone shoreface facies with multiple hardgrounds and firmgrounds. This sequence is capped by a hardground, as a sequence boundary. This hardground is well developed and cemented in the paleotopographic highs (Well-E, F and G). This hardground is gradually losing its harden toward the basin, toward north, and marked by a firmground.

This sequence has the most lateral variability of any of the HFSs. Above this HFS, the stratigraphy becomes more flat and layer-cake like.

5.1.2. HIGH-FREQUENCY SEQUENCE 2 (HFS 2)

This high-frequency sequence is 4.5 to 6.8 meters (15 to 22 feet) thick. The thinnest part of this sequence is located in the paleotopographic highs (Well-D, E and F) (Figure 5.1 and Enclosure 6.4, 6.5 and 6.6) and gets slightly thicker out of this area toward the north, north and south of these wells. This high-frequency sequence consists of a thin transgressive coated-grain grainstone at the top of the hardground/firmground as Transgressive Systems Tract. The thin transgressive coated-grain grainstone is overlain by *Pfenderina trochoidea* wackestone transgressive lagoon facies in the down-dip (north) area, *Thaumatoporella* wackestone facies in the paleotopographic highs (Well-D, E and F) and intraclast coated-grain grainstone as shoreface in the updip area (Well-F and G). All of these facies are capped by a thin *Pfenderina trochoidea* wackestone facies. The maximum flooding surface coincides with the thin *Pfenderina trochoidea* wackestone facies and it is overlain by the high-stand systems tract. The high-stand systems tract consists mainly of Thaumatoporella wackestone facies and by stromatoporoid wackestone/packstone facies in some areas. The high-stand systems tract is capped by firmground as a top sequence boundary.

5.1.3. HIGH-FREQUENCY SEQUENCE 3 (HFS 3)

This high-frequency sequence is the first high-frequency sequence in the high-stand systems tract of the Lower Fadhili composite sequence 1 (LFC1). This sequence is 2.2 to 3.6 meters (7.5 to 12 feet) thick (Figure 5.1). It is getting thinner toward the south (Well-G) (Enclosure 6.7) and thicker toward the north (Well-A) (Enclosure 6.1). This sequence consists of shallowing upward cycle and it is defined by Thaumatoporella wackestone facies with slightly stromatoporoid wackestone/packstone facies, which is overlain by coated-grain grain-dominated packstone, which is capped by firmground as a sequence boundary.

5.1.4. HIGH-FREQUENCY SEQUENCE 4 (HFS 4)

High-frequency sequence 4, up to 3.81 to 5 meters (12.5 to 16.5 feet) thick (Figure 5.1), is the upper most high-frequency sequence in the high-stand systems tract of the Lower Fadhili composite sequence 1 (LFC1). This sequence is defined by flooding surface over the high-stand systems tract of the underlying high-frequency sequence 3 (HFS 3). The flooding surface is marked by the distal transegressive *Pfenderina trochoidea* wackestone facies in the wells located out of the paleotopographic highs area, in the south (Well-F and G) (Enclosure 6.6 and 6.7), in the north (Well-A and B) (Enclosure 6.1 and 6.2), in the east (Well-I) (Enclosure 6.9), and in the west (Well-H) (Enclosure 6.8). At the paleotopographic highs (Well-C, D and E) (Enclosure 6.3, 6.4 and 6.5), the flooding is marked by stromatoporoid *Cladocoropsis* wackestone facies which is overlain by *Cladocoropsis* and sponge spicules rich wackestone facies as a high-stand systems tract, which is capped by a well cemented hardground as the top sequence boundary of the Lower Fadhili composite sequence 1 (LFC1) (Figure 5.6). The upper most part of the highstand of this high-frequency sequence HFS4 has been intensively burrowed starting from the hardground (the top sequence boundary) up to 1 meter (3.5 feet) below the hardground.

5.2. LOWER FADHILI COMPOSITE SEQUENCE 2 (LFC2)

This composite sequence 2 (LFC2) has variation in thickness (Figure 5.1 and 5.2). In the north (Well-A) the composite sequence is 10.3 meters thicker than in the south (Well-G). In the south (Well-G), this composite sequence is 18.6 meters (61.2 feet) thick.

In Qirdy area (Well-E and F), the thickness of this composite sequence is 21 meters (68.75 feet). In the middle of the Khurais field (Well-B, C and D), the thickness of this composite sequence is 23.6 meters (77.5 feet). In the far north (Well-A), the thickness of this composite sequence is 28.9 meters (85 feet). In the west (Well-H), the thickness of this composite sequence is 21 meter (70 feet). In the east (Well-I), this sequence is up to 24.3 meters (80 feet) (Figure 5.2).

This sequence is defined from the base by the well cemented hardground (Figure 5.6) which is the top boundary of the lower composite sequence (LFC1), and is defined from top by a major well cemented hardground with karstification feature (Figure 5.4). This composite sequence (LFC2) is made up of four upward-shallowing high-frequency sequences (from bottom-to-top): HFS5, HFS6, HFS7 and HFS8.

The Transgressive Systems Tract of this composite sequence consists mainly of a thick (0.3-1 meters) intraclast peloid coated-grain grainstone/grain-dominated packstone transgressive shoreface facies which overlie by hardground/firmground surfaces. The intraclast peloid coated-grain grainstone/grain-dominated packstone facies are interbedded with *Thaumatoporella Cladocoropsis* wackestone/packstone lagoonal facies. The high-stand systems tract of this composite sequence consists mainly of Stromatoporoid wackestone/packstone facies. The maximum flooding surface of LFC2 coincides with the maximum flooding surface of HFS6 at the base of the Stromatoporoid wackestone/packstone facies.

5.2.1. HIGH-FREQUENCY SEQUENCE 5 (HFS 5)

This high-frequency sequence, up to 6.8 meters (22.5 feet) (Figure 5.1), consists of an intraclast coated-grain grainstone transgressive shoreface facies as Transgressive Systems Tract which overlies the top of the hardground surface (Figure 5.6). The intraclast coated-grain grainstone transgressive shoreface facies is overlain by *Thaumatoporella Cladocoropsis* wackestone/packstone lagoonal facies with some Stromatoporoid facies especially at Well-C (Enclosure 6.3). The maximum flooding surfaces of this high-frequency sequence coincide with the base of *Thaumatoporella Cladocoropsis* wackestone/packstone lagoonal facies. The *Thaumatoporella Cladocoropsis* wackestone/packstone lagoonal facies is the high-stand system tract of this sequence. The upper most part of the high-stand systems tract of this sequence has been burrowed and capped by a firmground surface as sequence boundary.

5.2.2. HIGH-FREQUENCY SEQUENCE 6 (HFS 6)

The thickness of this sequence varies between 6.1 – 7 meters (20-23 feet) (Figure 5.1). The base sequence boundary is the firmground of top sequence boundary of (HFS 5). The transgressive systems tract of this sequence consists of two fining upward cycles and they are defined by thick intraclast coated-grain grainstone transgressive shoreface facies overlying *Thaumatoporella Cladocoropsis* wackestone lagoonal facies. The maximum flooding surface coincides with top of the *Thaumatoporella Cladocoropsis* wackestone lagoonal facies of the second cycle. The high-stand systems tract of this sequence is defined by Stromatoporoid wackestone/packstone facies. This sequence is capped by a sequence boundary marked by a firmground surface.

5.2.3. HIGH-FREQUENCY SEQUENCE 7 (HFS 7)

This sequence is a relatively small cycle and thickening northward. In the south (Well-G) (Enclosure 6.7), the thickness of this sequence is 3.4 meter (11.25 feet) (Figure 5.1). In the north (Well-A) (Enclosure 6.1), the thickness is 5.7 meter (18.7 feet). This sequence is bounded from the base by a weak firmground. This sequence consists of one shallowing cycles made up of Stromatoporoid wackestone/packstone facies. The Stromatoporoid wackestone/packstone facies in some areas is overlain by updip *Thaumatoporella* wackestone lagoonal facies. This sequence is capped by a thin high-stand peloid coated-grain grainstone only in the south area (Well-E, F and G) (Figure 5.1) and in this area the sequence is bounded from the top by firmground/hardground surface. The top boundary gets weaker toward the north.

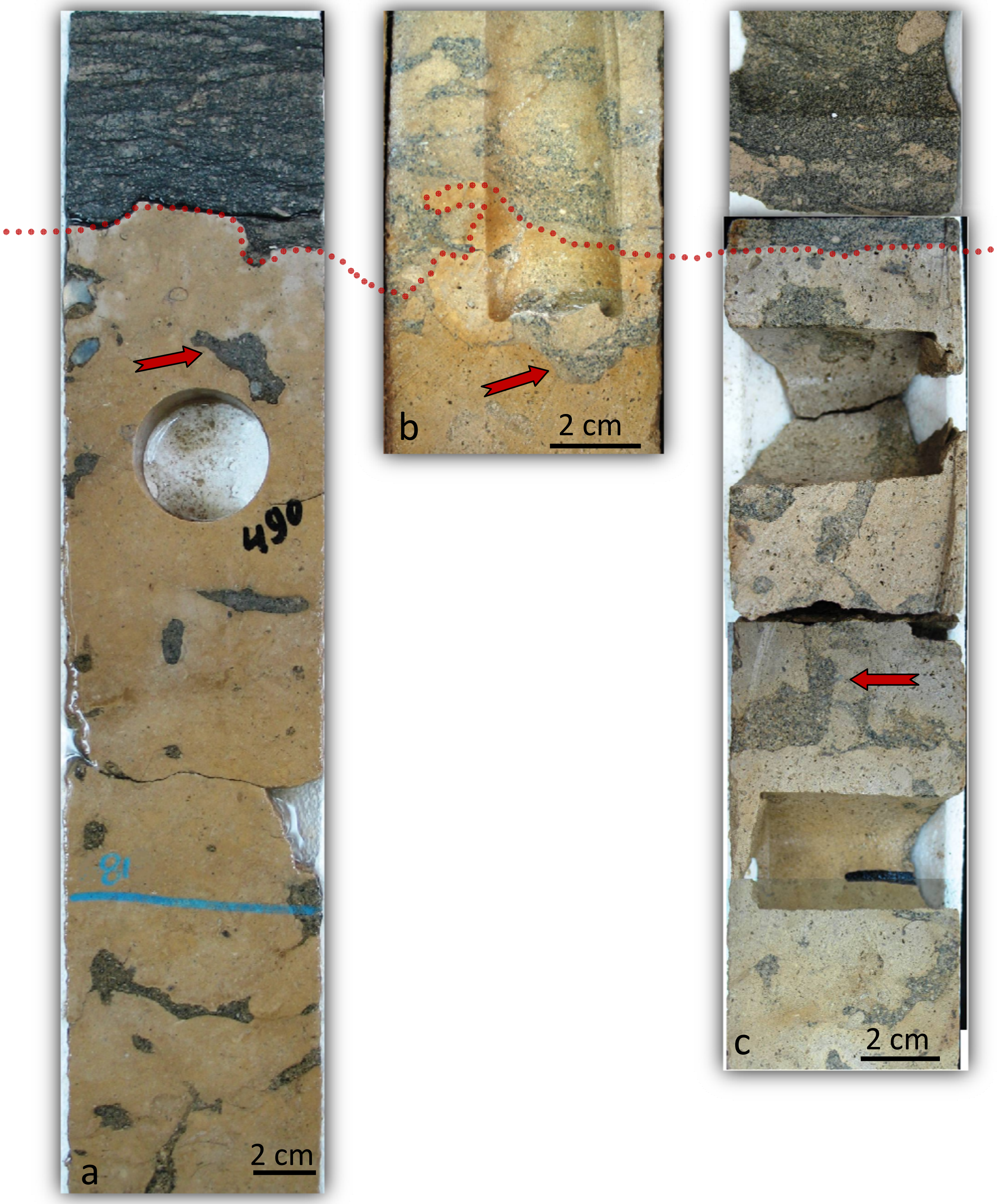


Figure 5.6. Core photos from different wells showing a cemented hardground/firmground (red dotted line). Beneath the hardground there are intensive burrows (red arrows) filled with peloid coated-grain grainstone from the above layer. This hardground is interpreted to extend for more than 100 km. Firmground and hardground are interpreted to be sequence and cycle boundaries. This hardground is the top sequence boundary of LFC1.

5.2.4. HIGH-FREQUENCY SEQUENCE 8 (HFS 8)

This sequence, up to 2.2 meters (7.5 feet) thick in the south (Well-G) and 4.5 meters (15 feet) thick in the north (Well-A) (Figure 5.1 and Enclosure 6.7 and 6.1), consists of a shallowing upward cycle. The sequence is defined by a thick proximal *Thaumatoporella* wackestone lagoonal facies only in the paleotopographic highs (Well-B, C, D and E). Out of the paleotopographic highs (Well-I) in the east and (Well-G) in the south, the sequence is defined by coarse and grainy Stromatoporoid packstone facies. Overall this facies is overlain by *Thaumatoporella* wackestone lagoonal facies, which is capped by a well cemented hardground. In the late high-stand systems tract, the sequence is dominated by a cemented intraclast coated-grain grainstone overlying the hardground surface. The cemented intraclast coated-grain grainstone consists of thin cycles capped by multiple hardgrounds and capped by the intensive karst feature as a top sequence boundary (Figure 5.4).

5.3. SEQUENCE STRATIGRAPHY DISCUSSION

The history of sequence succession of the Lower Fadhili reservoir is summarized in the following points:

- At the base of the study interval, green marl layers overlain and interbedded with well cemented ooid coated-grain intraclast grainstone. The uppermost cemented surface is interpreted to be an unconformity marking possibly a 1 million year time gap.
- The unconformity is the base sequence boundary of LFC1 and is marked by a karst surface with meteoric cementation.
- The base of LFC1 sequence is made up of proximal peloid coated grain grainstone and packstone facies that onlaps into the unconformity surface and distal *Pfenderina trochoidea* wackestone facies filling the accommodation space in the basin (Figure 5.1).
- The transgressive systems tract of LFC1 sequence is defined by a retrograding pattern and backstepping landward of the *Pfenderina trochoidea* wackestone facies and the MFS is picked in a thin layer of *Pfenderina trochoidea* wackestone facies that extends over the proximal facies. From this point upward the cycles and sequences correlate in a very flat “layer-cake” manner.
- In the HST, the abundance of *Pfenderina trochoidea* decreases and the abundance of sponge spicules and *Thaumatoporella* increases. There is an increase in graininess toward the top of the sequence. This may indicate for proximal lagoonal setting low water circulation. The LFC1 sequence is capped by a well cemented hardground as sequence boundary.

- The transgressive systems tract of LFC2 (Figure 5.1) has many transgressive surfaces in the base overlain by transgressive peloid coated-grain grainstone and packstone (reservoir) facies that fine upward. The maximum flooding surface of LFC2 corresponds to a thick stromatoporoid facies which indicates for open and well circulated marine environment.
- Toward the top of the HST, the abundance of *Thaumatoporella* increases in the high-stand system tract of LFC2, the abundance of stromatoporoids decreases upward and *Thaumatoporella* wackestone packstone facies becomes more dominant. The high frequency sequence thins upward (e.g., HFS8 in Well-G has thin cycles compared to the one below HFS7) and capped by well cemented hardground and karst surface as the upper sequence boundary. Above the boundary, green shale and marl was deposited.

CHAPTER 6

DISCUSSION

6.1. CLIMATIC INFLUENCE

Climate has a big control in carbonate sediments, type of facies, type of grains, fossils diversity, marine temperature, salinity and wave activities.

During Middle Jurassic, the Arabian basin was situated in warm equatorial latitude within approximately 10 degrees south the equator (Hussein, 1997). There is sedimentologic evidence for the climate during the Lower Fadhili deposition time. One piece of the evidences is the karst features. There are micro-karst features on top of the ooid peloids grainstone beach facies in the early transgressive system tract of LFC1 that are marked by meteoric cements and also the top sequence boundary of LFC2, which is marked by an extensive karst surface. Karst by definition is a physical structure formed by fresh water dissolution (Flügel, 2004). So, the karst surfaces indicate a humid climate for at least some of the time. There are some of the ooids in the beach and upper shoreface facies in the lower grainy part of LFC1 which are more likely to form in an arid climate. Thus the overall climate for the Lower Fadhili deposition in Khurais complex is interpreted to be semiarid.

Stromatoporoids, as mentioned in Chapter Four, are most likely to form in water with normal salinity. Therefore the area around the maximum flooding surface of

Lower Fadhili composite sequence 2 (LFC2) was not very restricted. *Thaumatoporella* becomes abundant at the top most part of the high-stand systems tract of LFC1 and LFC2. This observation implies that the water became shallower, the accommodation space got less, the water circulation got weaker and the salinity increased slightly.

6.2. SEQUENCE BOUNDARY

There are two types of sequence boundaries that have been recognized in the Lower Fadhili reservoir, Type 1 and Type 2. The major factor controlling the type of sequence boundaries is the falling of relative sea level related to the underlying sequence and the shelf margin.

Type 1 unconformities are interpreted to form when relative sea level falls beneath the shelf margin (Read, 1995). They are characterized by subaerial exposure and subaerial erosion, and a hinterland deposition above the underlying marine sequence. Therefore the sequence boundary here is unconformable. This type of sequence boundary is observed in the base sequence boundary of LFC1 (Figure 6.2) and the top sequence boundary of LFC2 as unconformity (Figure 6.1). The basal unconformity of the Lower Fadhili reservoir is marked by two sedimentological criteria: karst feature, which indicates a significant time of subaerial exposure (Calner et al, 2009), and evidence for meteoric cements (e.g., micro stalagtitic, meniscus and bladed isopachous cements) in the facies beneath the unconformity surface. In addition, a palynology study, made by Nigel P. Hooker (Saudi Aramco internal report No. 134, 2006), showed a hiatus between lower green-calcareous shale and the main body of the Lower Fadhili reservoir. The top unconformity, the top sequence boundary of LFCD2, is marked by two sedimentological criteria: green shale overlying carbonate layers (Figure 6.1) and penetration of green shale into the karstic caves (Figure 5.3) (Read, 1995).

Type 2 boundaries are interpreted to be formed with small sea level falls where the sea level fall does not exceed the shelf margin. They are characterized by no major shift basin ward in the shoreline position and facies, and no subaerial erosion is associated. Therefore the sequence boundary type 2 is conformable (Read, 1995). Type 2 is observed in the top sequence boundary of LFC1 (Figure 5.5).

Marine flooding surfaces record a rapid increase in water depth (Mulholland, 1998) and separate transgressive system tracts from underlying low-stand system tracts (Read, 1995) or high-stand systems tracts. Additionally, they separate a shallow marine facies from the deep marine facies. In this study, the marine flooding surface is interpreted to be the top boundary of the high-frequency sequence. In addition, a marine flooding surface is called transgressive surface (Read, 1995).

From previous studies, hardground surfaces are common in a shallow high-energy conditions and their frequency is decreasing away from the high-energy into the inner shelf. In the Bahamas for example, hardgrounds are probably related to high saturated $CaCO_3$ water surface. The $CaCO_3$ concentration is increased by degassing of CO_2 from the marine water, under certain conditions. One of these conditions is high wave agitated environment and tidal energy (Moore, 1989). Hardgrounds are considered to be the final stage of a shallowing upward sequence (Purser, 1969). In this study, hardground surfaces have been used as a marker for parasequence boundary and type 2 sequence boundary. The hardgrounds are better developed in the late highstand and early transgressive parts of sequences and poorly developed around the maximum flooding surfaces of cycles and sequences.

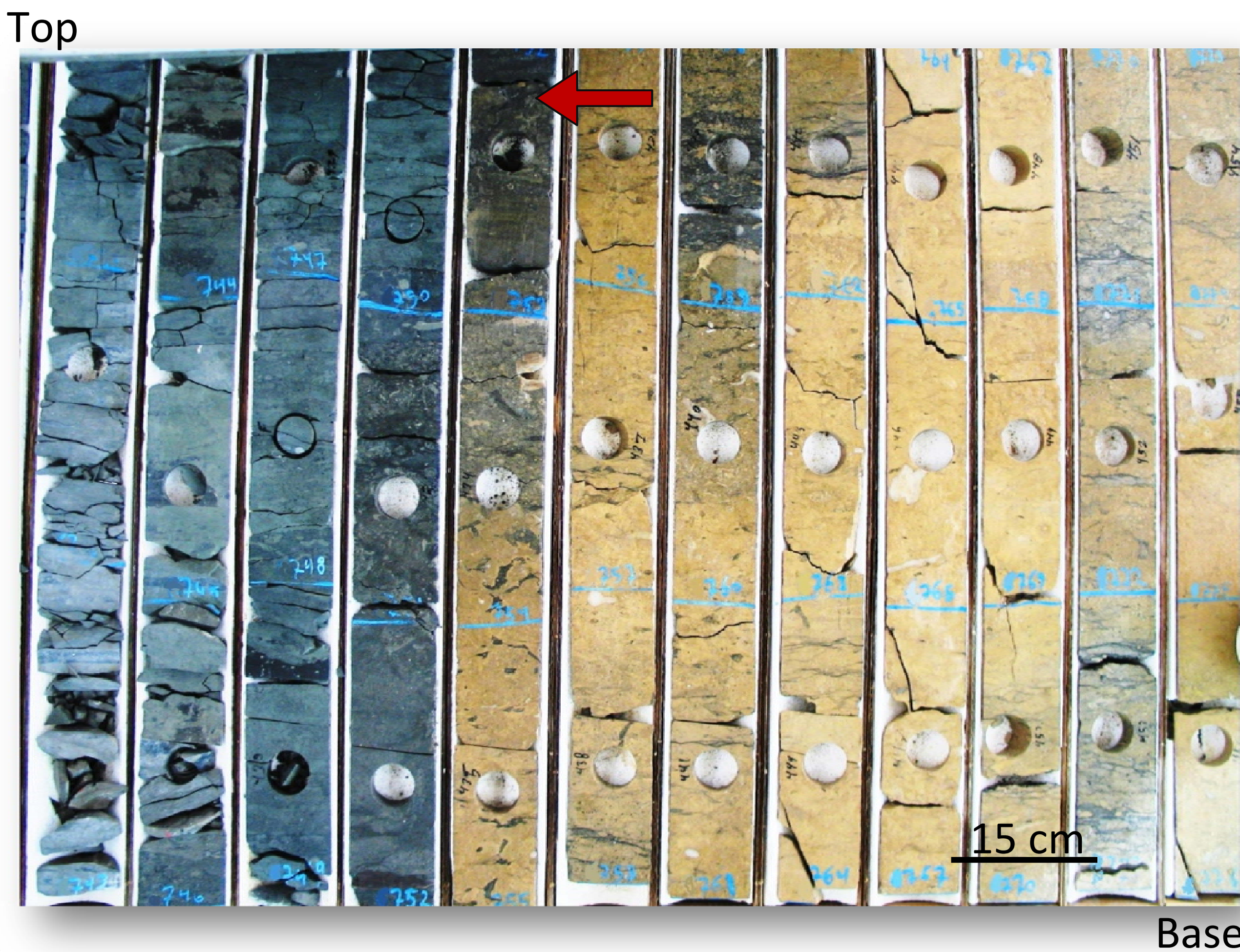


Figure 6.1 Core photograph of the top sequence boundary of LFC2 from Well-G. The red arrow points to the location of the major karst surface (Figure 5.3). This photo shows how the green calcareous shale overlay the carbonate limestone.

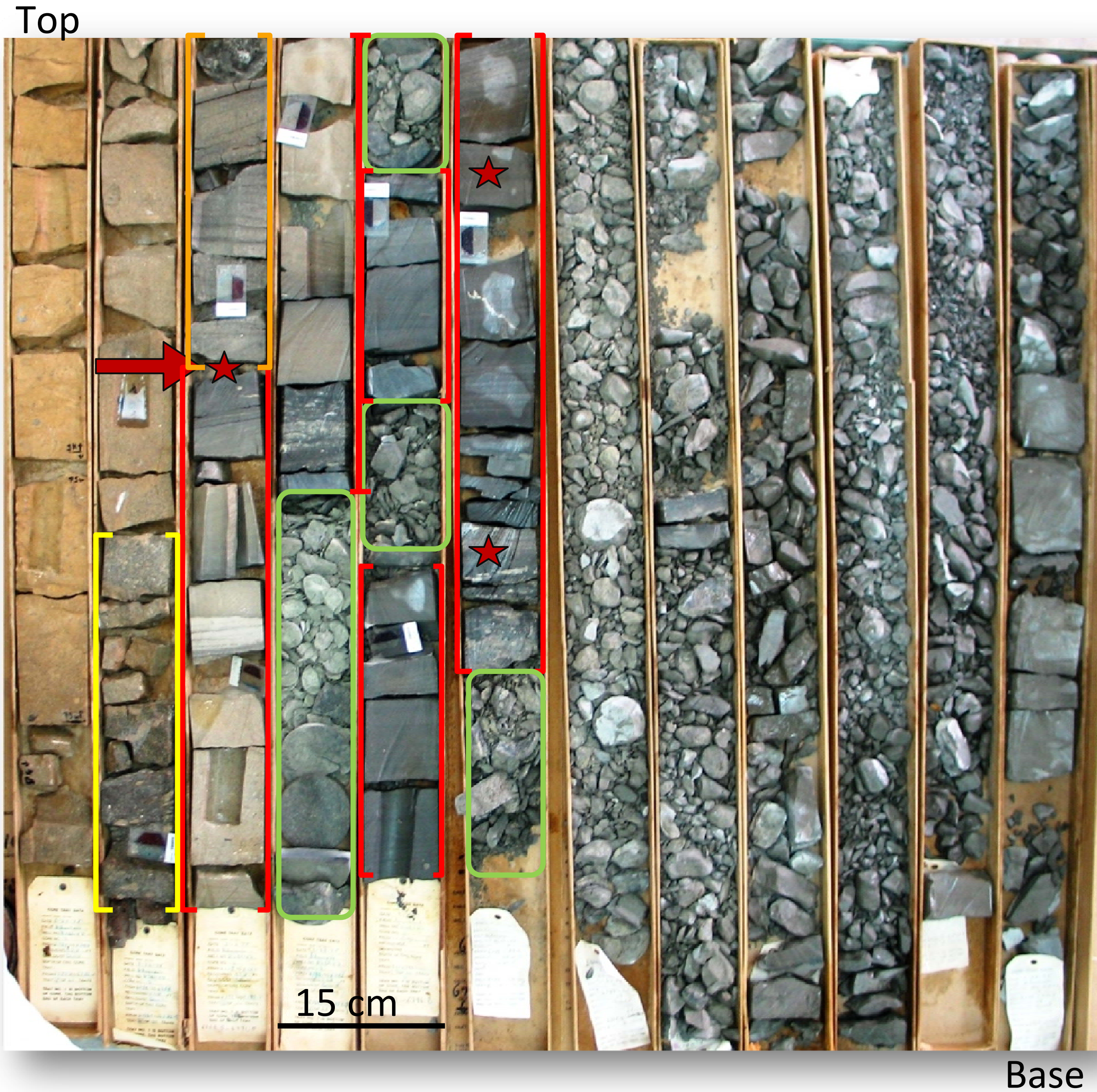


Figure 6.2 Core photograph for the base sequence boundary of LFC1 from Well-C. The red arrow points to the sequence boundary, the unconformity. Beneath the sequence boundary there is ooid coated grain grainstone beach facies (between the red lines). The ooid coated grain grainstone beach facies are totally cemented due to the exposure surface (red stars). The micro karst and the meteoric cements with early ferroan calcite cement have been observed beneath all exposure surfaces. The beach facies, fine grain low angle cross-bedding grainstone (between the red lines) is capped by the unconformity surface. Then during the transgression the unconformity is overlain by upper shoreface with coarse high-angle cross-bedding grainstone (between the orange lines). The upper shoreface is overlain by lower shoreface coated-grain peloids structureless grainstone (between yellow lines). Then the lower shoreface is overlain by the most distal facies which is the *Pfenderina trochoidea* wackestone/mudstone facies.

6.3. SYSTEM TRACTS

6.3.1 TRANSGRESSIVE SYSTEM TRACT (TST)

The high-frequency sequences of Transgressive System Tract TST have certain criteria. One of them is that the shallow facies should show retrogradational stacking patterns which means the shallow marine facies as well as distal marine facies would show progressive backstepping upward in the cross section. Second, the boundaries of high-frequency sequences of the TST are showing the slightest development of exposure surfaces due to the rising of relative sea level. Other criterion is that the high-frequency sequences are thick and contain more distal marine facies (Read, 1995).

All of these criteria are presented in the transgressive system tract of LFC1 in the sequence stratigraphic cross-section (Figure 5.1, in Chapter 5). The *Pfenderina trochoidea* wackestone/mudstone facies are progressively backstepping upward from north to south overlaying updip the peloid coated-grain grainstone and packstone facies. During transgression, the peloid coated-grain grainstone and packstone is fining upward and capped by hardground/firmground surface. The thickest cycles in the Lower Fadhili reservoir are in the transgressive system tract of LFC1 especially in north toward the basin and they contain the most distal facies, which is *Pfenderina trochoidea* wackestone/mudstone facies. The transgressive system tract of LFC2 has a lot of transgressive surface of erosion overlain by a thick transgressive shoreface facies that is fining- and dipping-upward.

6.3.2 MAXIMUM FLOODING SURFACES (MFS)

The maximum flooding surface is separating the Transgressive System Tract (TST) from the High-Stand System Tract (HST) and it is characterized by a landward extension of a distal marine facies over a shallow water facies (Read, 1995).

The most distal marine facies, *Pfenderina trochoidea* wackestone/mudstone facies, in the cross section (Figure 5.1) shows an extension over the shallow marine facies represented by landward (north-south) backstepping capped by thin layer. The thin layer of *Pfenderina trochoidea* wackestone/mudstone facies is the maximum flooding surface (MFS) of LFC1. The maximum flooding surface of LFC2 corresponds to a thick stromatoporoid facies which indicates for open and well circulated marine.

6.3.3 HIGH-STAND SYSTEM TRACT (HST)

During the High-Stand System Tract, the accommodation space starts to decrease compared to the Transgressive System Tract. The criteria of the HST high-frequency sequences are: first the shallow water facies become more dominant upward in the high-frequency sequences. Second, the high-frequency sequences are thinning upward sequences. Third, the facies become relatively restricted upward compared to the TST facies (Read, 1995).

In the high-stand system tract of LFC1, the *Pfenderina trochoidea* wackestone/mudstone facies in the succession above the MFS are decreased upward marked by northward backstepping. The *Pfenderina trochoidea* wackestone/mudstone facies disappeared in the late high-stand system tract of LFC1. This disappearance is because the accommodation space had decreased and the shallow marine facies got dominated upward. The dominant shallow water facies in the HST of LFC1 is Thaumatoporella wackestone/mud-dominated packstone facies with less common Cladocoropsis and more sponge spicules. HFS4, the last high-frequency sequence in LFC1, has more small cycles compared to the underling high-frequency sequence HFS3. This cycle difference indicates for the thinning upward high-frequency sequence. The abundance of Thaumatoporella and the absence of the Stromatoporoid in the late HST of LFC1 as well as LFC2 may indicate for lagoonal setting with low water circulation.

In the high-stand system tract of LFC2, the open marine facies Stromatoporoid decreased upward and the Thaumatoporella wackestone packstone facies had become more dominant. The high-frequency sequence got thinning upward. For example, the HFS8 in Well-G has thin cycles compared to the one below HFS7.

CONCLUSIONS

The Lower Fadhili Reservoir in Khurais complex, up to 48 meters (157 feet) thick, is composed of a hierarchy of sequences and cycles. There are two large-scale sequences numbered in stratigraphic order: composite sequence 1 (LFC1) and composite sequence 2 (LFC2). Each of these is composed of four upward-shallowing high-frequency sequences (HFS) (Figure 7.1), which are in turn composed of multiple smaller scale cycles. The base of the Lower Fadhili reservoir, the base of LFC1, is bounded by an unconformity marked by karst surface and meteoric cementation. The top of the Lower Fadhili reservoir, the top of LFC2, is bounded by a sequence boundary marked by karst surface.

The sequences of the Lower Fadhili reservoir are made up of five facies arranged spatially and integrated in a depositional model. The facies (in order from proximal to distal) are: skeletal coated-grain grainstone upper shoreface, peloid coated grain grainstone and packstone lower shoreface, *Thaumatoporella* wackestone inner lagoon, stromatoporoid wackestone/packstone outer lagoon and *Pfenderina trochoidea* wackestone/mudstone transgressive lagoon. There are two more facies that have been recognized from the Lower Fadhili cores and are not genetically related to the Lower Fadhili reservoir facieses and sequences. These facies are: argillaceous mudstone and calcareous shale marginal marine and cemented ooid coated-grain intraclast grainstone beach facies.

The Lower Fadhili reservoir in the Khurais complex formed in a shallow carbonate ramp, which very gently dips toward the north and east of Khurais complex. The prevailing depositional environment in this reservoir is shallow-marine lagoon. There was a paleo-topographic high during the early transgression of LFC1, which is located in Qirdy Area. After that, the sediments filled the accommodation space and the paleotopography of the Lower Fadhili became almost flat.

The peloid coated-grain grainstone and packstone facies has the best reservoir quality because it has interparticle porosity. The interparticle porosity is well connected in this facies. This facies occurs in the transgressive systems tract of the composites sequences as transgressive shoreface and gets thicker in the transgressive systems tract of LFC2. Sponge-spicule Thaumatoporella wackestone, Stromatoporoid Wackestone/Packstone and *Pfenderina trochoidea* wackestone facies have poor reservoir quality because the dominant porosity type in those facies is microporosity. Cemented ooid coated-grain intraclast grainstone beach and argillaceous mudstone and calcareous shale facies are non-reservoir facies and acting as seals.

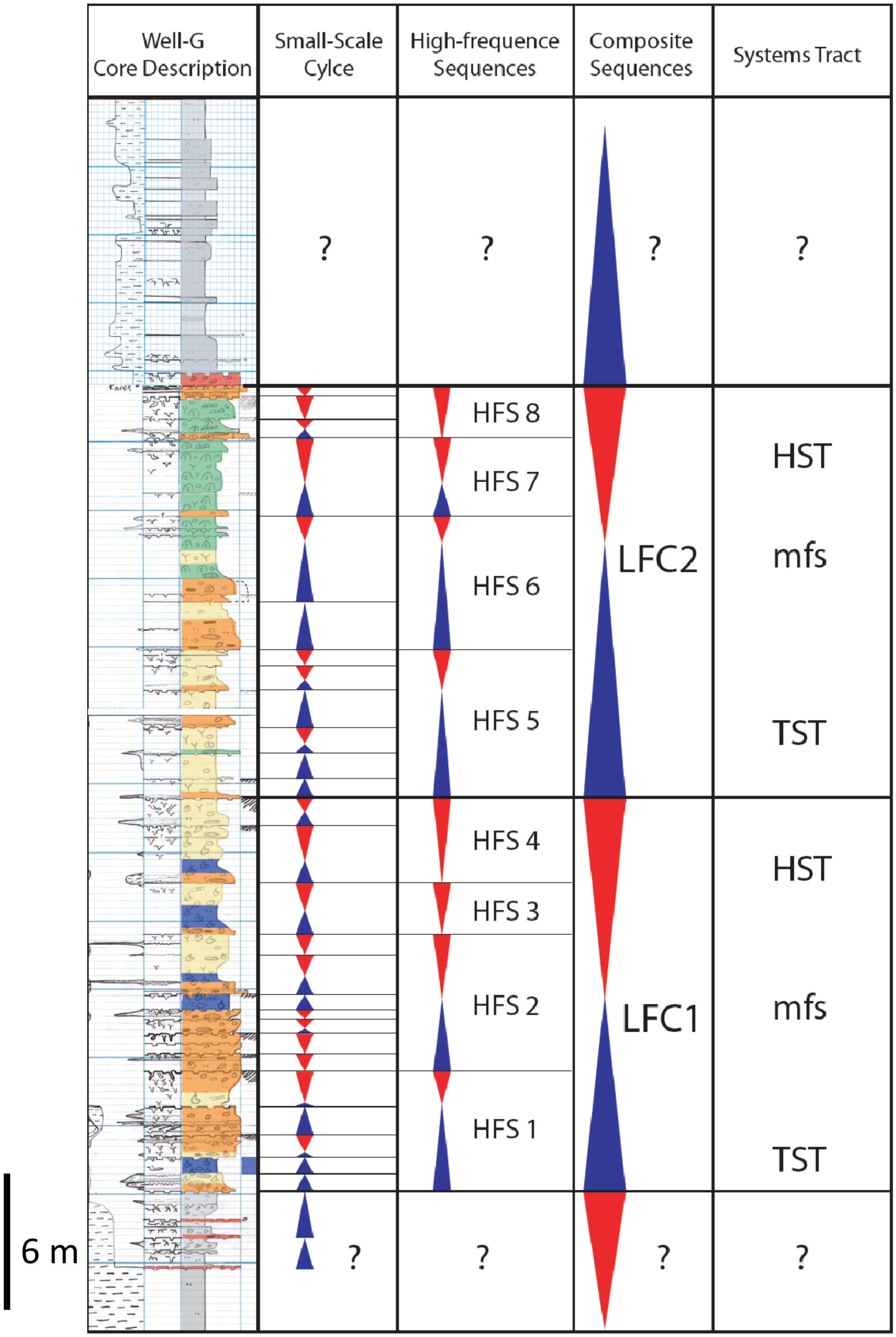


Figure 7.1 Sequence stratigraphy hierarchy of Lower Fadhili reservoir in Khurais complex.

RECOMMENDATIONS

- This study provides the sedimentological description, the sequence stratigraphy and the depositional model of the Lower Fadhili reservoir in Khurais area. Establishing additional regional sequence stratigraphic correlation between the Khurais area and the nearby fields out of the Arabian Basin and/or at Rimthan and Qatar Arch will help to understand the regional depositional model of the Lower Fadhili reservoir. This information will also help in mapping the barriers that were deposited in the lagoonal environment.
- It is recommended to use the result of this study as a framework for reservoir characterization studies and by integrating multiple data sets from different disciplines (e.g., production data, reservoir pressure data, and petrophysical data).
- Most of the ooid coated-grain intraclast grainstone beach facies, beneath the base unconformity, are completely cemented with early ferrone calcite cement and meteoric cement. Few thin sections are available from this facies. It is important to know the source of the early ferrone calcite cement and the diagenetic processes associated with this facies.
- Hughes (2004) described benthic foraminifera species and identified the palaeoenvironmental model for Middle to Upper Jurassic reservoirs based on micropalaeontological studies of hundreds of thin sections. Describing Lower Fadhili biocomponents in Khurais complex from thin sections and using his study as a guide will help in understanding the depositional environment/setting of the facies defined herein.

- Isotope studies for the Lower Fadhili reservoir are recommended for a better understanding of the diagenesis, climate, and stratigraphy.
- Many morphological types of stromatoporoid have been identified from the cores in this study (for example laminar, domical, dendroid and encrusting). Defining the relationship between stromatoporoid morphologies and their depositional environment will help in understanding the depositional model of the Lower Fadhili reservoir.

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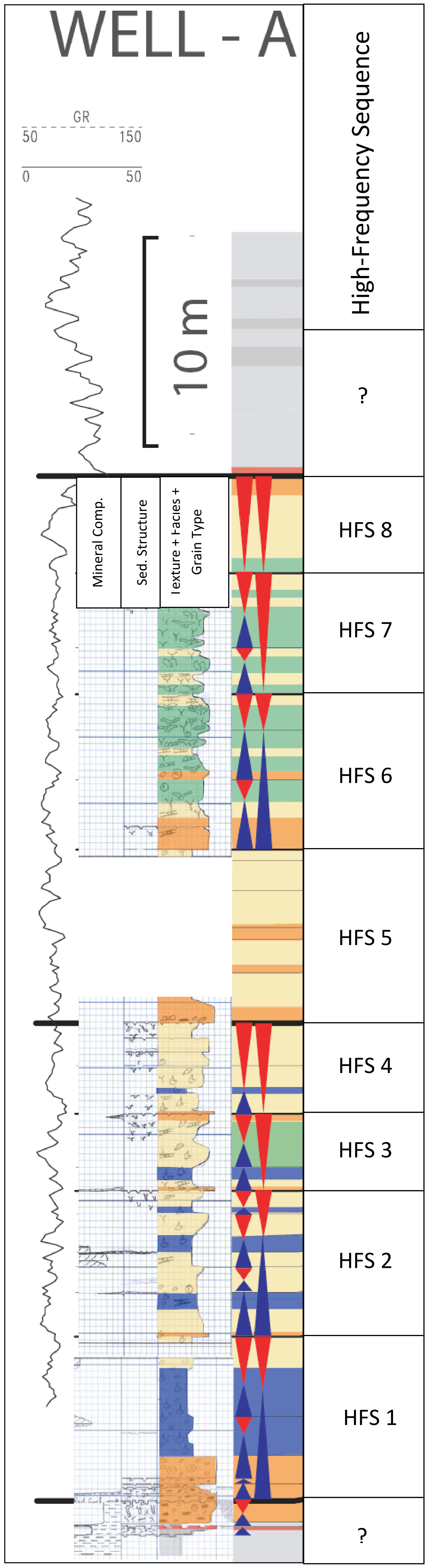
Enclosure 6.1



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-A.

Legend

Facies:

- *Pfenderina trochoidea* wackestone (Transgressive Lagoon)
- Stromatoporoid Wackestone/Packstone (Outer Lagoon)
- *Thaumatoporella* Wackestone (Inner Lagoon)v
- Peloid Coated Grain Grainstone and Packstone (Lower Shoreface)
- Skeletal-Coated Grain Grainstone (Upper Shoreface)
- Cemented Ooid Coated-Grain Intraclast Grainstone (Beach)
- Argillaceous Mudstone and Calcareous Shale (Marginal Marine)

Sedimentary Structures:

- Chondrities Burrows
- Argillaceous Stylolite
- Cross Bedding
- Burrows
- Hardground
- Firmground

Fossils and Grain Types:

- Coated Grain
- *Thaumatoporella*
- Intraclast
- *Pfenderina trochoidea*
- Peloid
- Stromatoporoid
- Ooid
- *Cladocoropsis*
- Coral
- Sponge Spicules

Lithologies:

- Dolomite Mineral
- Calcareous Green Shale
- Silty Argillaceous Layers

Parasequences:

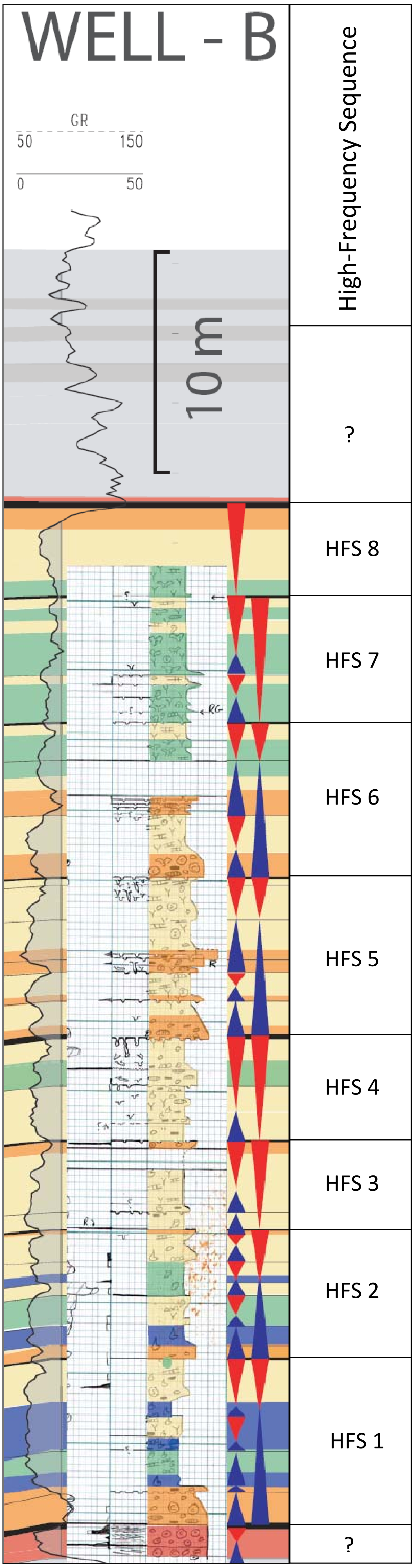
SB

Decreasing Accommodation

Increasing Accommodation

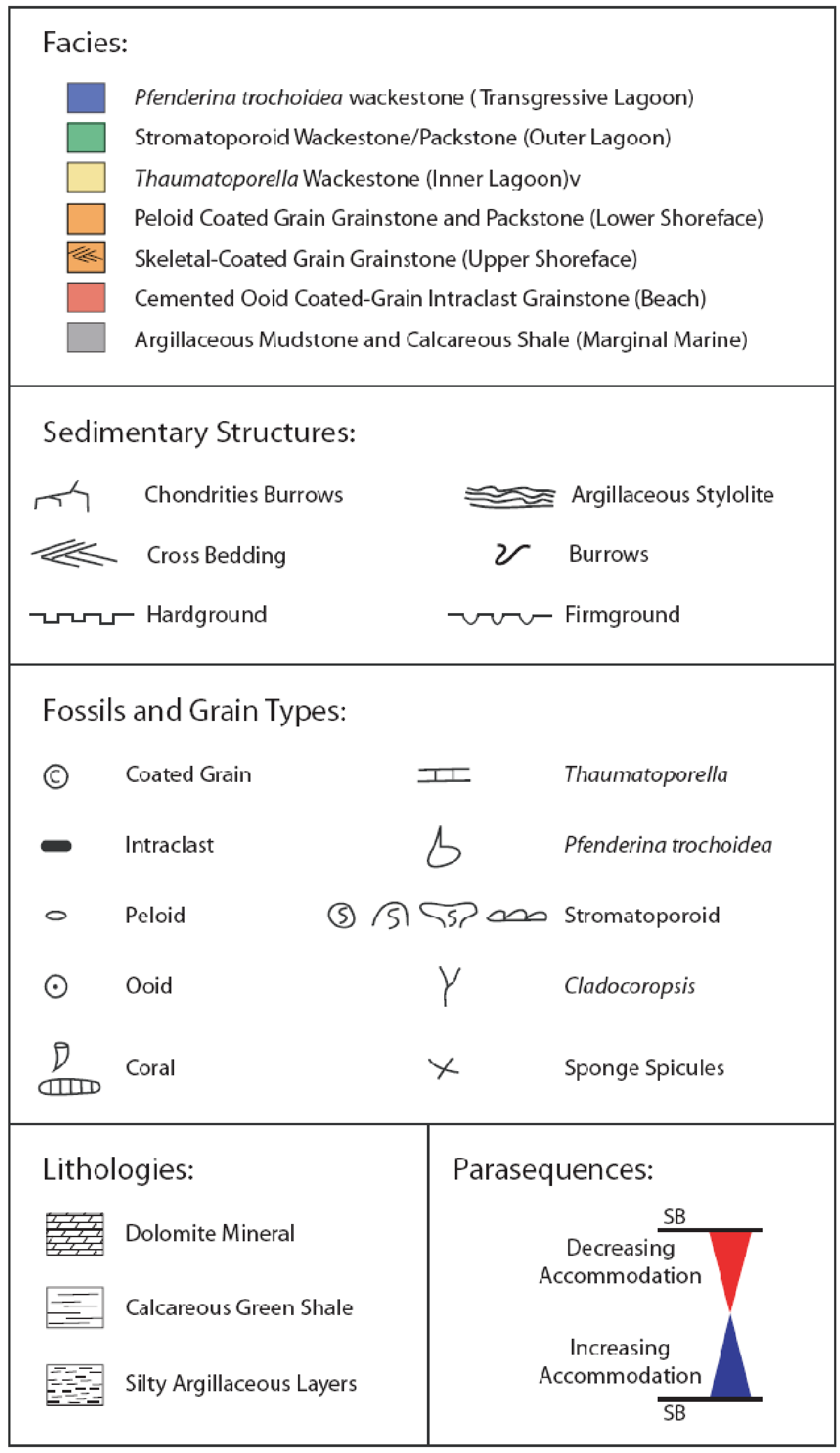
SB

Enclosure 6.2

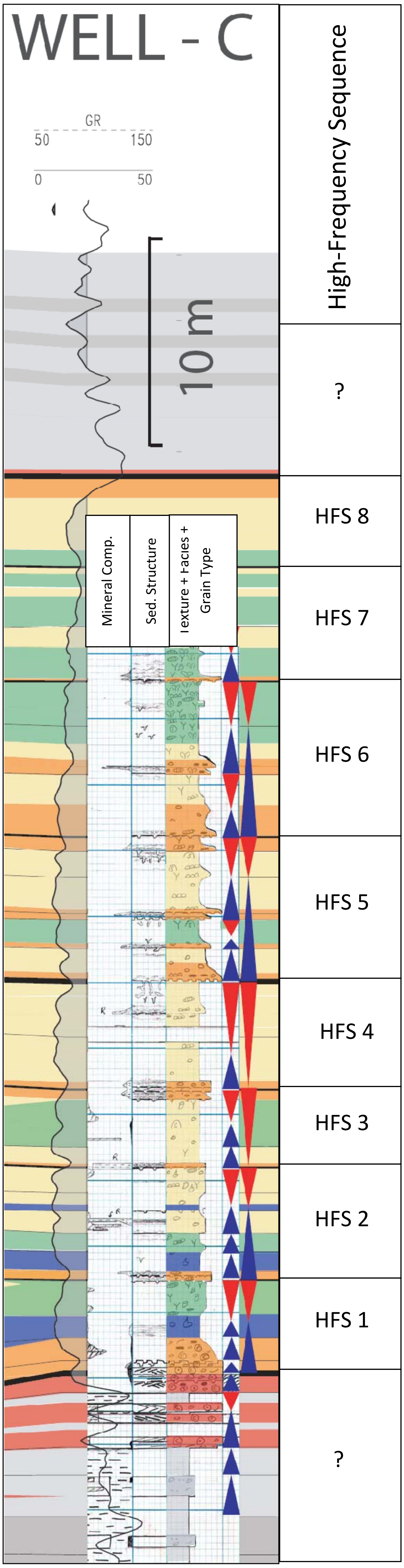


Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-B.

Legend

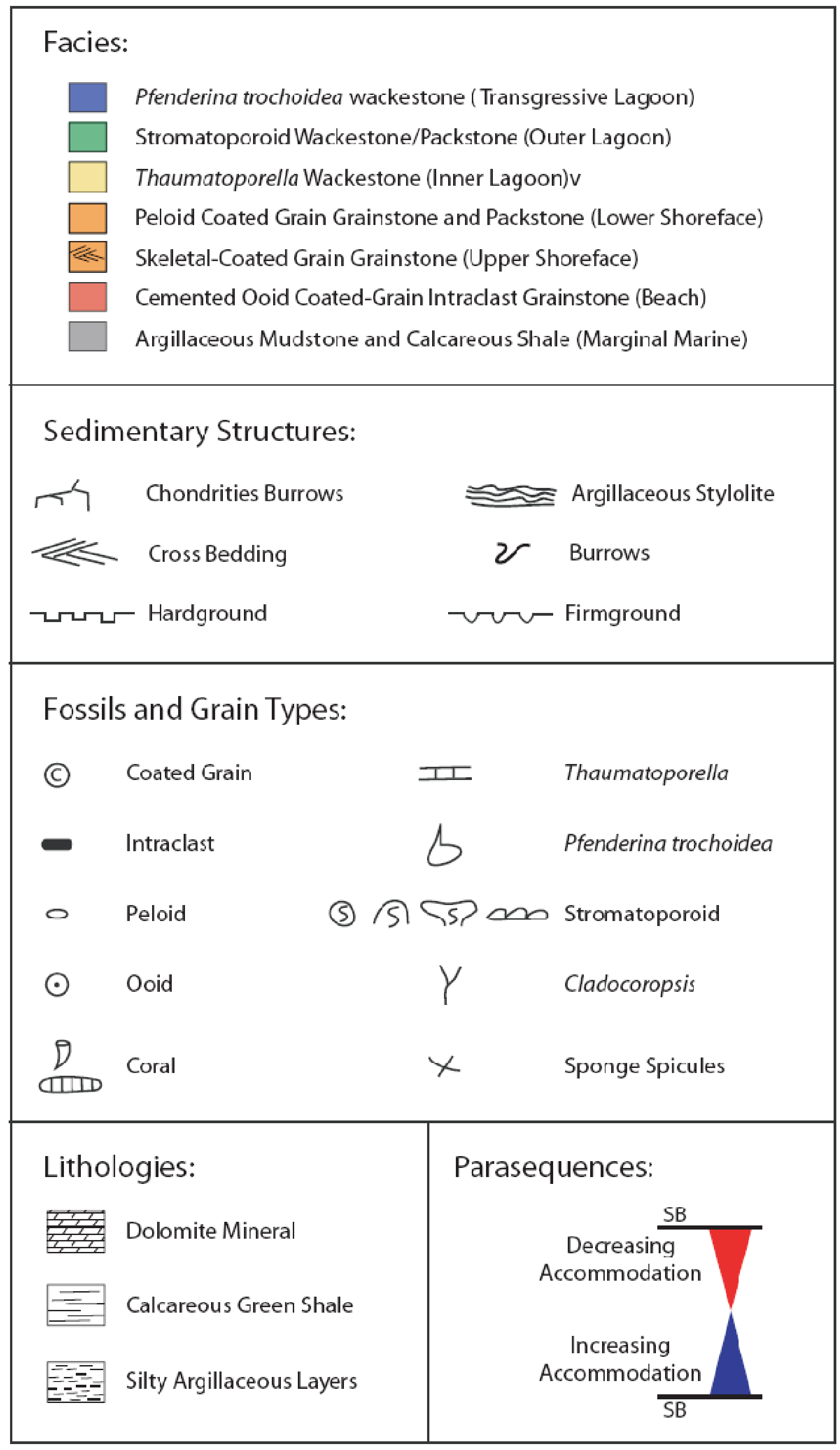


Enclosure 6.3

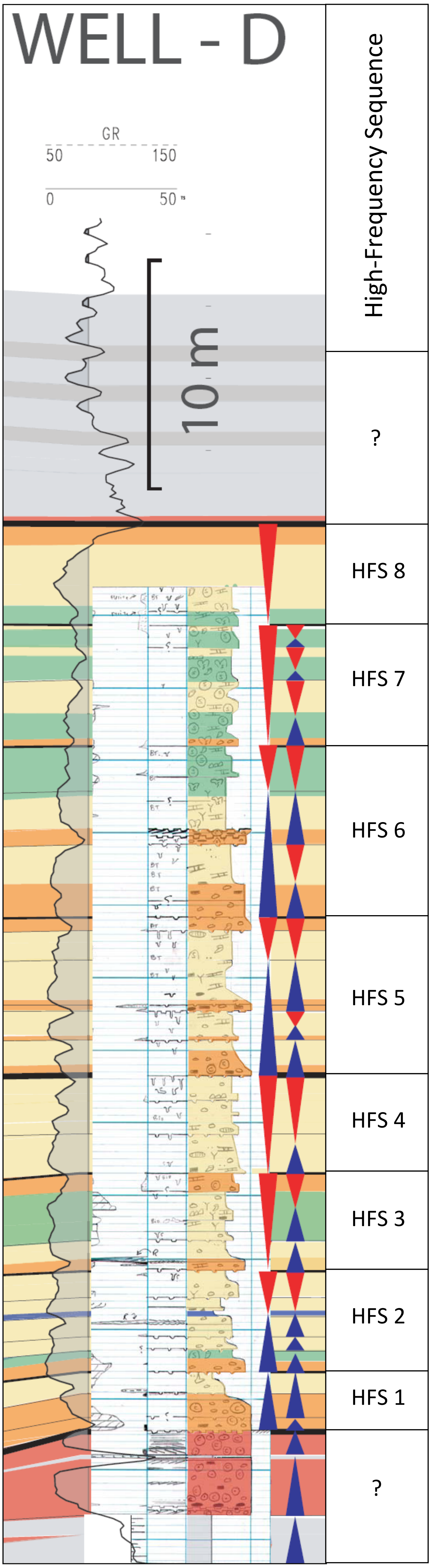


Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-C.

Legend



Enclosure 6.4



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-D.

Legend

Facies:

- *Pfenderina trochoidea* wackestone (Transgressive Lagoon)
- Stromatoporoid Wackestone/Packstone (Outer Lagoon)
- *Thaumatoporella* Wackestone (Inner Lagoon)v
- Peloid Coated Grain Grainstone and Packstone (Lower Shoreface)
- Skeletal-Coated Grain Grainstone (Upper Shoreface)
- Cemented Ooid Coated-Grain Intraclast Grainstone (Beach)
- Argillaceous Mudstone and Calcareous Shale (Marginal Marine)

Sedimentary Structures:

- Chondrities Burrows
- Argillaceous Stylolite
- Cross Bedding
- Burrows
- Hardground
- Firmground

Fossils and Grain Types:

- Coated Grain
- *Thaumatoporella*
- Intraclast
- *Pfenderina trochoidea*
- Peloid
- Stromatoporoid
- Ooid
- *Cladocoropsis*
- Coral
- Sponge Spicules

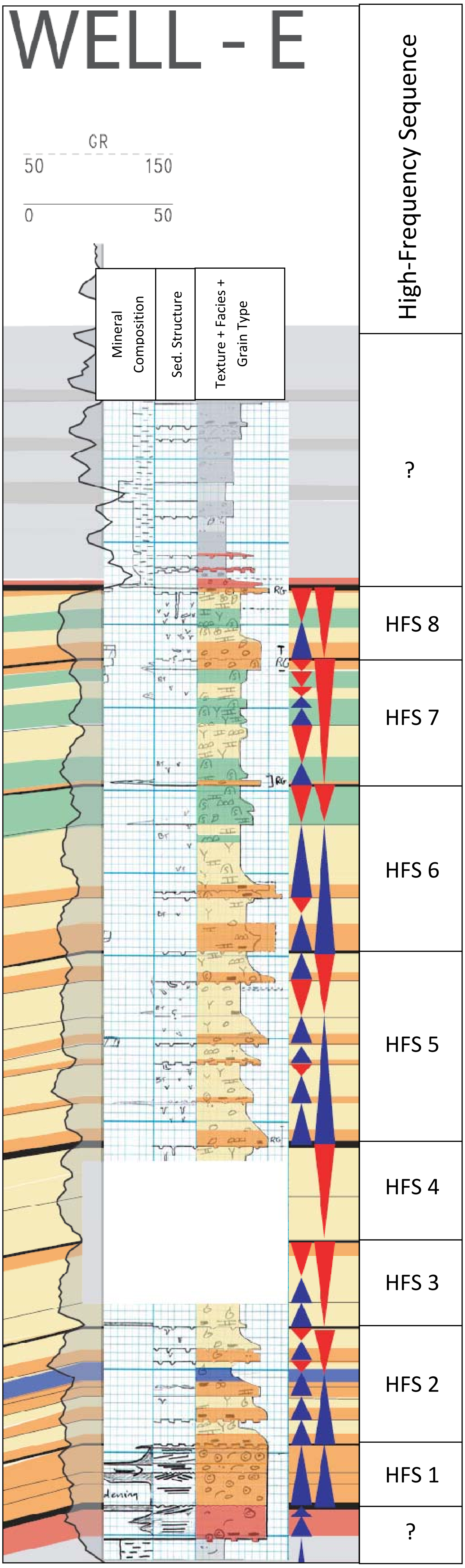
Lithologies:

- Dolomite Mineral
- Calcareous Green Shale
- Silty Argillaceous Layers

Parasequences:

SB
Decreasing Accommodation
Increasing Accommodation
SB

Enclosure 6.5



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-E.

Legend

Facies:

- *Pfenderina trochoidea* wackestone (Transgressive Lagoon)
- Stromatoporoid Wackestone/Packstone (Outer Lagoon)
- *Thaumatoporella* Wackestone (Inner Lagoon)v
- Peloid Coated Grain Grainstone and Packstone (Lower Shoreface)
- Skeletal-Coated Grain Grainstone (Upper Shoreface)
- Cemented Ooid Coated-Grain Intraclast Grainstone (Beach)
- Argillaceous Mudstone and Calcareous Shale (Marginal Marine)

Sedimentary Structures:

- Chondrities Burrows
- Argillaceous Stylolite
- Cross Bedding
- Burrows
- Hardground
- Firmground

Fossils and Grain Types:

- Coated Grain
- *Thaumatoporella*
- Intraclast
- *Pfenderina trochoidea*
- Peloid
- Stromatoporoid
- Ooid
- *Cladocoropsis*
- Coral
- Sponge Spicules

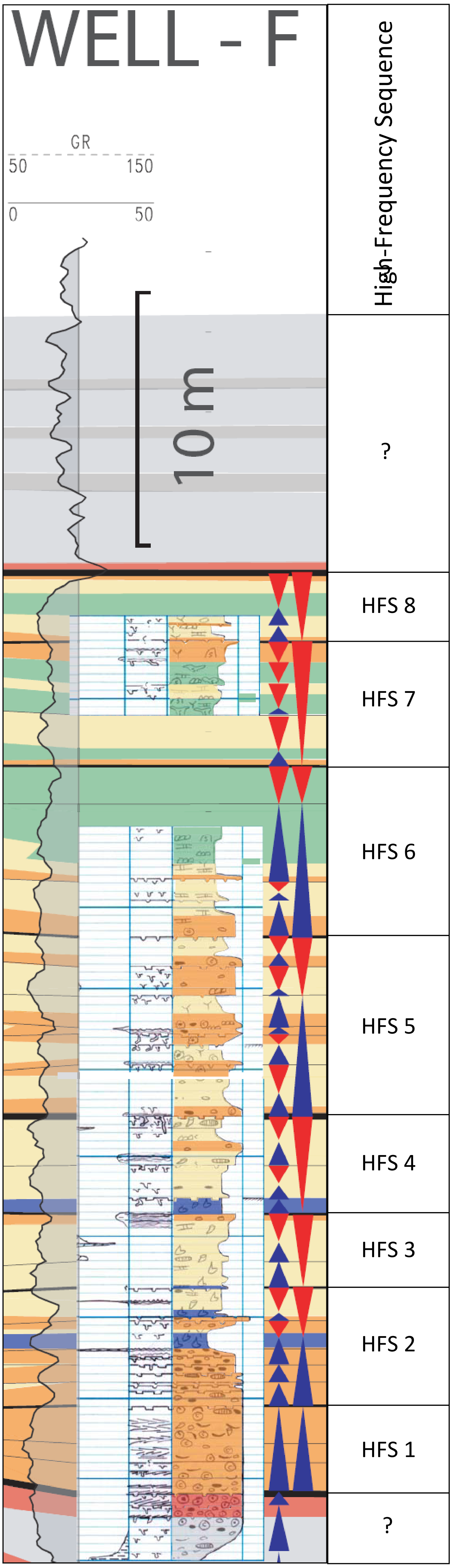
Lithologies:

- Dolomite Mineral
- Calcareous Green Shale
- Silty Argillaceous Layers

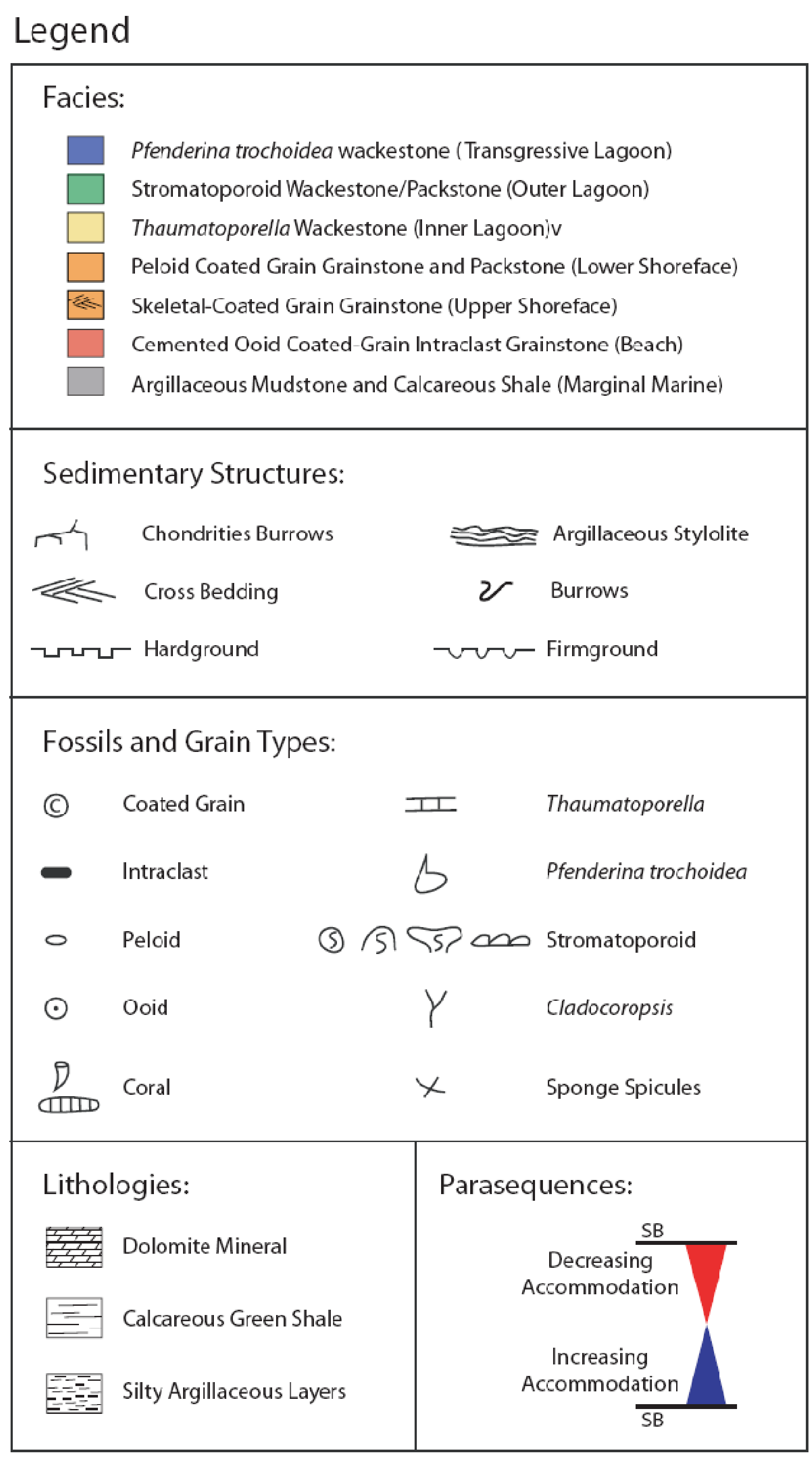
Parasequences:

- SB
- Decreasing Accommodation
- Increasing Accommodation
- SB

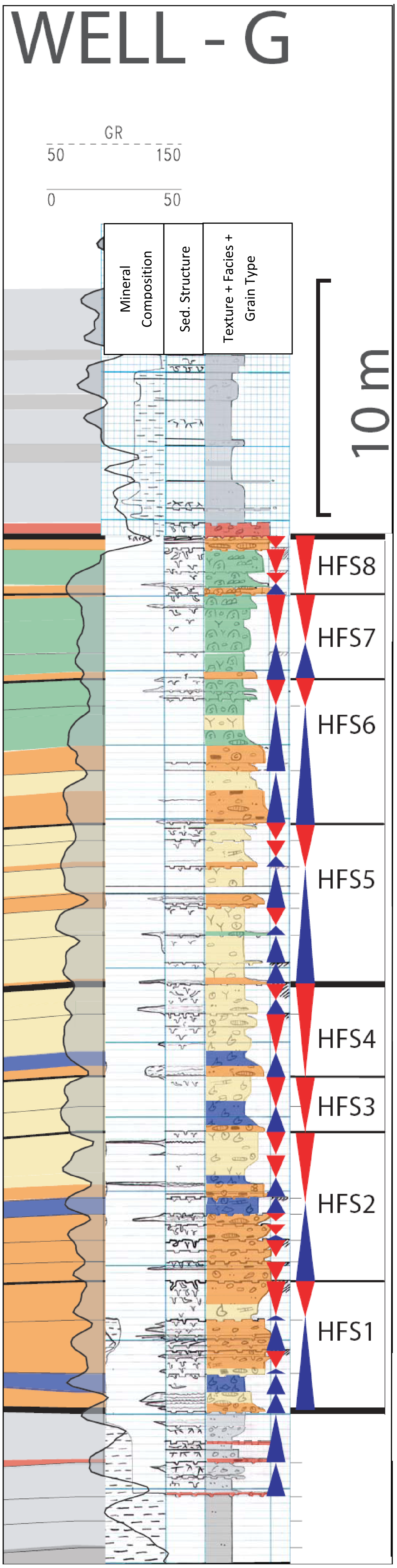
Enclosure 6.6



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-F.



Enclosure 6.7



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well G.

Legend

Facies:

- *Pfenderina trochoidea* wackestone (Transgressive Lagoon)
- Stromatoporoid Wackestone/Packstone (Outer Lagoon)
- *Thaumatoporella* Wackestone (Inner Lagoon)v
- Peloid Coated Grain Grainstone and Packstone (Lower Shoreface)
- Skeletal-Coated Grain Grainstone (Upper Shoreface)
- Cemented Ooid Coated-Grain Intraclast Grainstone (Beach)
- Argillaceous Mudstone and Calcareous Shale (Marginal Marine)

Sedimentary Structures:

- Chondrities Burrows
- Argillaceous Stylolite
- Cross Bedding
- Burrows
- Hardground
- Firmground

Fossils and Grain Types:

- Coated Grain
- *Thaumatoporella*
- Intraclast
- *Pfenderina trochoidea*
- Peloid
- Stromatoporoid
- Ooid
- *Cladocoropsis*
- Coral
- Sponge Spicules

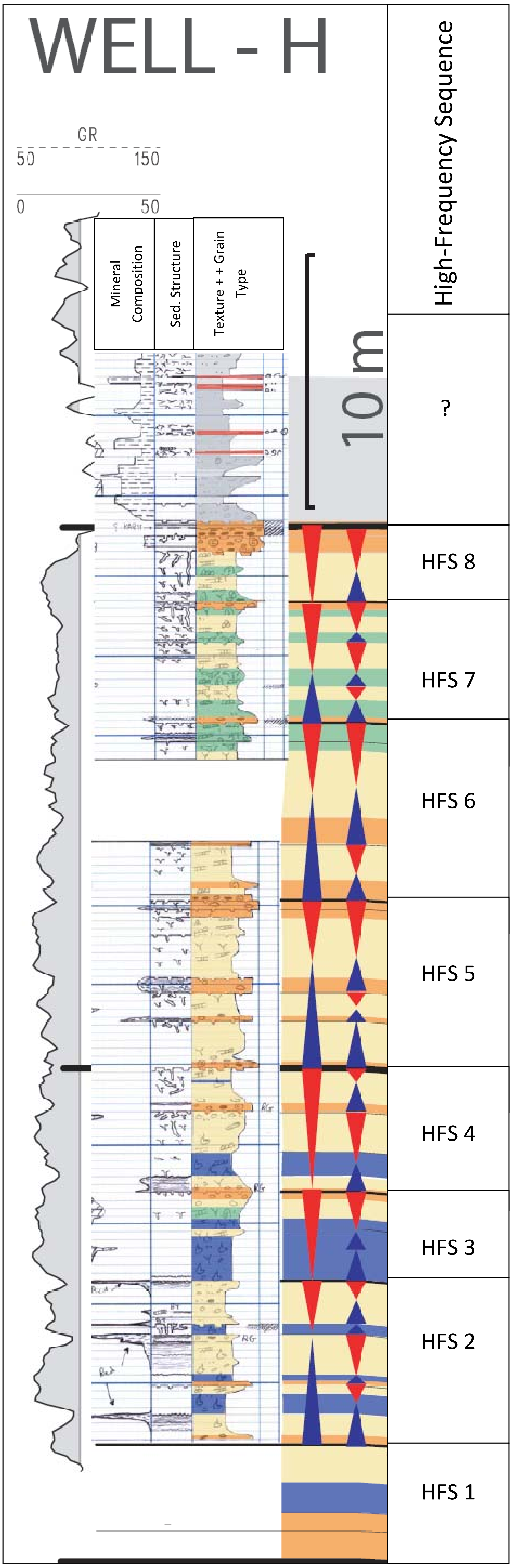
Lithologies:

- Dolomite Mineral
- Calcareous Green Shale
- Silty Argillaceous Layers

Parasequences:

- SB
- Decreasing Accommodation
- Increasing Accommodation
- SB

Enclosure 6.8



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-H.

Legend

Facies:

- *Pfenderina trochoidea* wackestone (Transgressive Lagoon)
- Stromatoporoid Wackestone/Packstone (Outer Lagoon)
- *Thaumatoporella* Wackestone (Inner Lagoon)v
- Peloid Coated Grain Grainstone and Packstone (Lower Shoreface)
- Skeletal-Coated Grain Grainstone (Upper Shoreface)
- Cemented Ooid Coated-Grain Intraclast Grainstone (Beach)
- Argillaceous Mudstone and Calcareous Shale (Marginal Marine)

Sedimentary Structures:

- Chondrities Burrows
- Argillaceous Stylolite
- Cross Bedding
- Burrows
- Hardground
- Firmground

Fossils and Grain Types:

- Coated Grain
- *Thaumatoporella*
- Intraclast
- *Pfenderina trochoidea*
- Peloid
- Stromatoporoid
- Ooid
- *Cladocoropsis*
- Coral
- Sponge Spicules

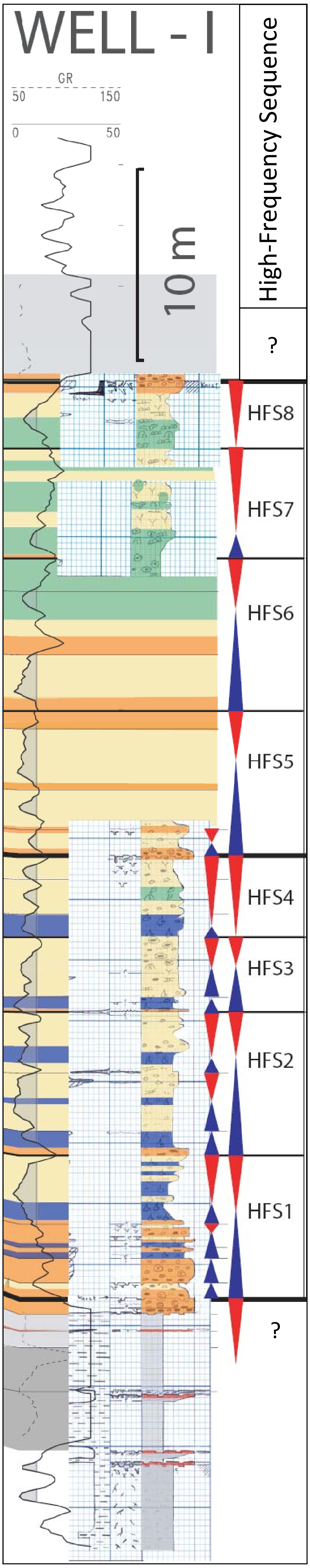
Lithologies:

- Dolomite Mineral
- Calcareous Green Shale
- Silty Argillaceous Layers

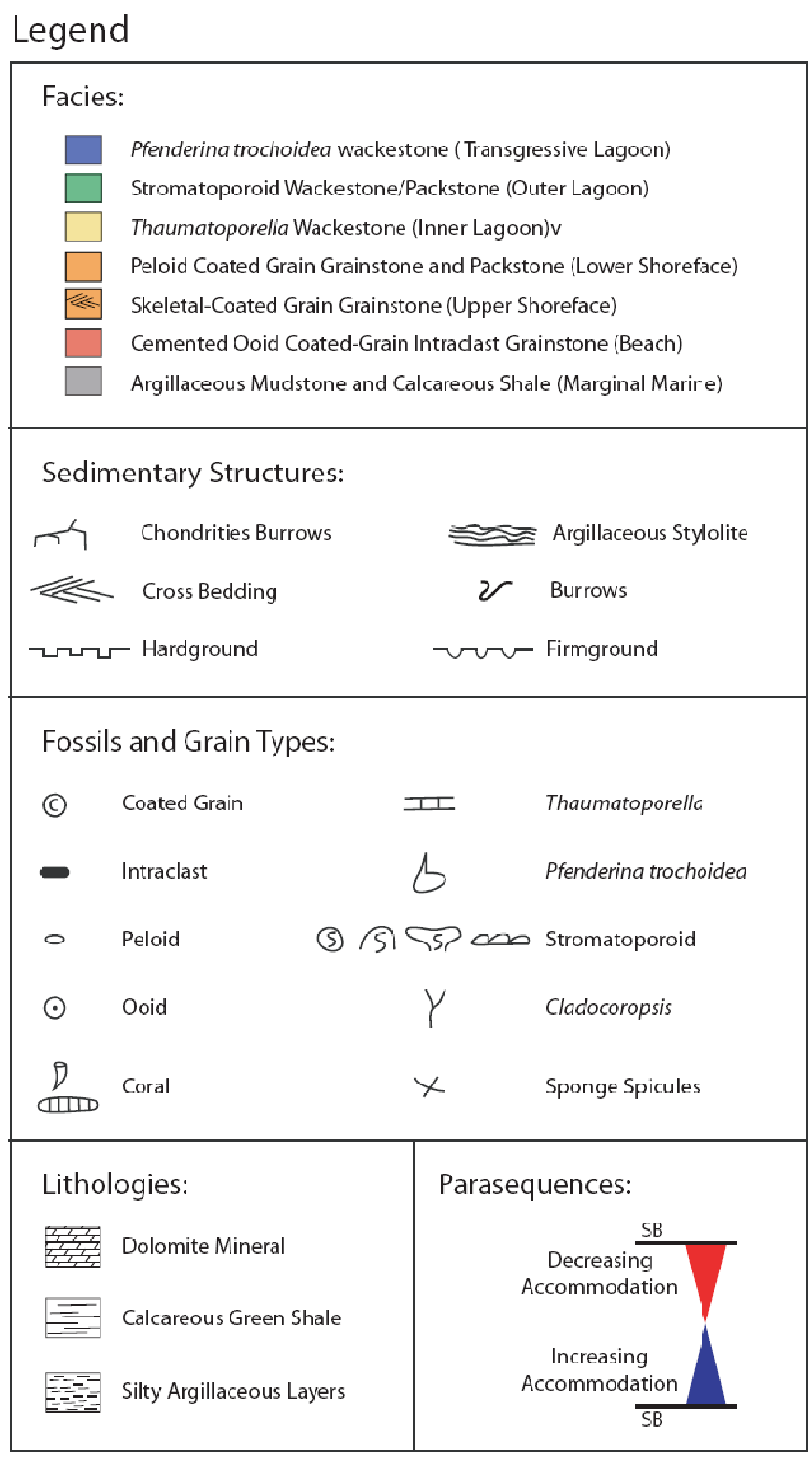
Parasequences:

- SB
- Decreasing Accommodation
- Increasing Accommodation
- SB

Enclosure 6.9



Core description, borehole gamma ray, facies interpretation, and high-frequency sequence stratigraphy in Well-I.



VITA

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